Report

Harvesting Carbon: Exploring BECCS as a Climate Solution for ASEAN

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Authors:
Lintang Ambar Pramesti, Muhammad Anis Zhafran Al Anwary,
Zahrah Zafira, Monika Merdekawati

Designer:
Bayu Jamalullael, Lintang Ambar Pramesti

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ASEAN Centre for Energy

Soemantri Brodjonegoro II Building, 6th Fl.
Directorate General of Electricity
Jl. HR. Rasuna Said Block X-2, Kav. 07-08
Jakarta, 12950, Indonesia

Tel. (62-21) 527 9332 | Fax. (62-21) 527 93350
E-mail: secretariat@aseanenergy.org
www.aseanenergy.org

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The topic of carbon capture and storage (CCS) holds strategic importance within ASEAN's energy transition agenda. CCS is recognised in the ASEAN Plan of Action for Energy Cooperation (APAEC) Phase II: 2021–2025 as a key component of the transition to a low-carbon economy. Specifically, CCS is addressed under **Programme Area No. 3: Coal and Clean Coal Technology (CCT)**. Within this framework, **Outcome-Based Strategy No. 1 aims to "Promote the Role of CCT and CCUS towards Energy Transition and a Low-Carbon Economy."** Furthermore, **Action Plan 1.3** seeks **to develop a strategic coal report and explore the potential of clean coal technology and CCU/S to support a low-carbon energy system**.

This publication is part of ACE's ongoing efforts to support ASEAN's energy transition by facilitating informed discussions on bioenergy with carbon capture and storage (BECCS) as a potential climate solution for the region. ACE hopes that this report serves as a valuable resource for policymakers, industry stakeholders, and researchers in advancing sustainable energy strategies across ASEAN.

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Executive Summary

BECCS (Bioenergy with Carbon Capture and Storage) stands out as a pivotal technology in achieving climate targets, offering a dual benefit: generating renewable energy while actively capturing and storing carbon emissions. Its versatility extends across multiple sectors, including biofuels, energy generation, and heavy industries, positioning it as a highly promising solution for a low-carbon future.

ASEAN is a region with abundant biomass resources, such as agricultural residues and forestry by-products, possessing significant potential to implement this technology. According to the 8th ASEAN Energy Outlook (AEO8), Southeast Asia could reach 55.34 GW of energy capacity from bioenergy under the baseline scenario, and might exceed 100 GW under the carbon-neutral scenario, with Indonesia, Thailand, and Viet Nam as the largest contributors. Regarding storage, research from the National University of Singapore indicates that the region has sufficient effective geological capacity to store CO_2 emissions from various stationary sources.

Despite its potential, implementing this technology comes with several challenges. BECCS could introduce additional emissions through its supply chain, including production, transportation, and processing. It also demands large amounts of land and resources, such as water and fertiliser, potentially diverting these resources away from crops. Ensuring sustainable feedstock availability adds to these challenges. The implementation of BECCS requires complex handling and, in many cases, significant investment to build the necessary infrastructure.

For carbon capture and storage, the primary challenges include a lack of regulatory frameworks, the high investment required to retrofit existing infrastructure, and the complexity of CO_2 transportation. To address these challenges, ASEAN must prioritise sustainable biomass supply to ensure long-term viability, while enhancing the technological and economic feasibility of BECCS through public-private partnerships and financial incentives.

Efforts should focus on addressing environmental and social impacts to avoid additional emissions or negative societal consequences that could undermine the technology's carbon reduction benefits. Furthermore, strengthening infrastructure, transportation, and storage capacity by identifying suitable storage sites, exploring decentralised storage solutions, fostering multilateral agreements for CO_2 transport, and promoting research and development tailored to individual countries' needs will be essential for the successful implementation of BECCS in the region.

Setting the Stage: Purpose and Scope

Report Objectives

Bioenergy with Carbon Capture and Storage (BECCS) has yet to be developed or implemented in the ASEAN region. However, it holds significant potential for advancing the region's carbon neutrality goals.

Carbon Neutrality Scenario outlined in the 8th ASEAN Energy Outlook (AEO8) underscores the role of Carbon Capture and Storage (CCS) technologies, including BECCS, in achieving ASEAN's climate targets. Additionally, CCS is recognised in the ASEAN Plan of Action for Energy Cooperation (APAEC) Phase II: 2021–2025, as a key component of the transition to a low-carbon economy.

Specifically, CCS is addressed under Programme Area No. 3: Coal and Clean Coal Technology (CCT). Within this framework, Outcome-Based Strategy No. 1 aims to "Promote the Role of CCT and CCUS towards Energy Transition and a Low-Carbon Economy." Furthermore, Action Plan 1.3 seeks to develop a strategic coal report and explore the potential of clean coal technology and CCU/S to support a low-carbon energy system [1].

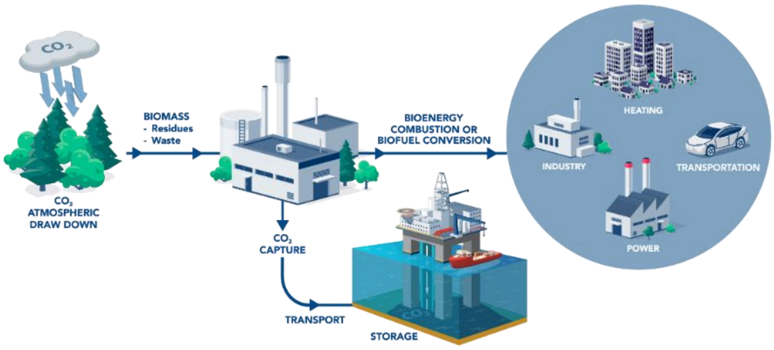
Fundamentals of BECCS

BECCS is an emerging two-step technique for carbon removal to address climate change. The first step involves converting biomass—organic material from sources such as agricultural by-products, forestry residues, and municipal waste—into energy in the form of heat, electricity, or fuel. This step is known as the "bioenergy" phase. The second step, "carbon capture and storage," captures the CO_2 emissions produced during bioenergy generation and stores them in geological formations or long-lasting products.

Technologically, BECCS should be seen as a sub-category of the broader CCS field. CCS technologies have been operational in various forms for decades and are considered mature, particularly in relation to the capture, transportation, and storage of CO_2 [2]. However, since these technologies were largely developed for fossil fuel combustion, adapting them to biomass-based systems is necessary due to the distinct properties of biomass as a fuel. Biomass differs significantly from fossil fuels, such as coal or natural gas, in terms of fuel properties and the composition of flue gasses [3][4].

Additionally, CCS applications vary widely, not only between fossil and biogenic CO_2 sources, but also with regard to the industrial processes. For example, capturing CO_2 from a coal power station with one large point source of emissions differs greatly from capturing CO_2 in a steel mill, where emissions are spread across multiple sources [5]. Similarly, capturing highly concentrated CO_2 from bioethanol fermentation is less costly and energy-intensive, as compared to capturing CO_2 from a biomass combustion process [3][4][6][6].

Figure 1. BECCS Value Chain



Source: Babcock

BECCS Process

1. **Bioenergy Generation**

   Bioenergy is produced by converting various forms of biomass into energy. Plants naturally absorb CO_2 during growth, making the CO_2 released during combustion part of a carbon-neutral cycle. To ensure sustainability, biomass must be responsibly sourced, ideally from regenerating or replanting materials. In many cases, bioenergy feedstock is derived from agricultural residues (like sugarcane waste), dedicated energy crops (such as fast-growing willows), or managed forests. Other emerging sources include algae cultivation and municipal organic waste [7].

   Bioenergy is typically generated by burning biomass to produce a high-pressure steam that drives turbines for electricity generation. This process can also use energy-dense biomass forms like compressed wood pellets, which can replace coal in existing power plants [7]. Additionally, biofuels like bioethanol and biodiesel are produced from biomass and used as renewable alternatives to gasoline and diesel. The bioethanol production process involves fermenting the sugars in plant material with yeast, resulting in the creation of ethanol and carbon dioxide [8]. Biodiesel is made from vegetable oils, animal fats, or recycled cooking grease through transesterification. It is used in diesel engines and heating systems, offering similar environmental benefits [9].

2. **Carbon Capture**

   In BECCS, carbon capture is primarily a post-combustion process, where solvents extract CO_2 from flue gases produced during biomass combustion. When gas is compressed, it occupies less volume, and even less when it is liquefied, solidified, or hydrated. Consequently, captured CO_2 is typically compressed and liquefied before being transported to storage sites, transforming it into a supercritical fluid. In bioethanol production, CO_2 is produced during the fermentation process, resulting in a near-pure stream of CO_2 that requires minimal processing before storage [7].

3. **Carbon Storage**

   Once captured, the CO_2 is injected—typically in a supercritical fluid state—into porous geological formations, such as depleted natural gas reservoirs, coal beds, or saline aquifers. This means it is at a temperature and pressure where it exhibits properties of both a liquid and a gas, meaning it is dense like a liquid, but able to flow like a gas [10]. The storage process allows for the permanent sequestration of CO_2. Over time, CO_2 may react chemically with surrounding minerals, ensuring long-term stability through mineral storage [7].

BECCS in Global Climate Strategy

Addressing climate change demands immediate and decisive action to limit global temperature rise in line with the Paris Agreement. The agreement sets a clear goal: keeping global warming well below 2°C while striving to limit it to 1.5°C.

However, pathways outlined by the Intergovernmental Panel on Climate Change (IPCC) indicate that emission reductions alone are insufficient to meet these targets. This challenge is especially pronounced in hard-to-abate sectors such as heavy industry, aviation, and shipping, where decarbonisation remains complex. At the same time, the global carbon budget—the maximum allowable emissions to limit warming—is shrinking rapidly. In this context, BECCS emerges as a critical technology. By enabling carbon dioxide removal (CDR), BECCS plays a vital role in achieving the ambitious climate objectives set forth in international agreements [11].

BECCS stands out among negative emissions technologies for its potential scalability and compatibility with existing industrial and energy systems. By integrating carbon capture with bioenergy production, BECCS can leverage existing infrastructure in sectors such as power generation and bioethanol production, making it a viable option for widespread adoption [12]. Its dual capability to produce renewable energy and sequester carbon makes it an attractive solution for countries seeking to balance economic growth with environmental commitments.

Moreover, BECCS provides flexibility in deployment, making it suitable for diverse contexts, from retrofitting existing power plants to developing new facilities designed for bioenergy and carbon capture. This adaptability not only enhances its appeal for developed economies seeking to modernise infrastructure, but also makes the technology accessible for emerging economies seeking low-carbon development pathways.

BECCS presents an opportunity to promote equity in global climate action. Regions with abundant biomass resources, particularly in developing countries, are well-positioned to benefit from its deployment [13]. In addition to contributing to global carbon removal, these nations can gain from technology transfer, economic diversification, and job creation in sectors ranging from agriculture to advanced bioenergy production. However, the implementation of BECCS must be carefully managed to prevent potential trade-offs, such as competition for land, water, and food resources, which could undermine its sustainability and social acceptability.

In scenarios where global temperature changes exceed 1.5°C, BECCS offers a practical pathway to reverse excess emissions and stabilise the climate [14]**.** The IPCC has consistently included BECCS in its pathways for limiting warming, recognising its central role in addressing overshoot risks, while supporting long-term climate stabilisation. By enabling the large-scale removal of atmospheric CO_2, BECCS can act as a safety net, buying time for societies to accelerate the transition to net-zero emissions.

While BECCS holds significant potential, its large-scale implementation faces several challenges. Ensuring the sustainability of biomass supply chains, minimising the energy intensity of carbon capture processes, and guaranteeing the long-term security of CO_2 storage are critical priorities. BECCS serves as an indispensable tool in the global climate strategy, bridging the gap between emission reductions and the need for large-scale carbon removal. It uniquely combines renewable energy production with carbon sequestration, offering a viable pathway to achieve net-negative emissions.

As countries work toward meeting the Paris Agreement's goals, BECCS has the potential to play a transformative role in balancing economic development with environmental sustainability. However, its success will depend on sustained global collaboration, strong policy support, and continued innovation to ensure its deployment aligns with broader climate and equity goals [15].

Evolution and Development

1. **Early 2000s: Concept Begins**
   Kenneth Möllersten, during his PhD research, explored ways to reduce CO_2 emissions in Sweden's pulp and paper industry, a key sector. His focus was on applying carbon capture and storage (CCS) technology to cut emissions, with the idea that industries could gain financial incentives from the Kyoto carbon emissions trading system, introduced under the Kyoto Protocol to encourage emission cuts.

2. **2000: GHGT Conference**
   Möllersten first presented his ideas on BECCS at the 5th Greenhouse Gas Control Technologies (GHGT) conference in Cairns, Australia. He and his PhD supervisor, Jinyue Yan, examined how pulp mills could use biomass and CCS to produce electricity, industrial heat, and achieve negative emissions. This marked the early thinking about CCS combined with biomass.

3. **2001: Collaboration with Michael Obersteiner**
   After Möllersten's talk in Cambridge, Michael Obersteiner, a scientist from IIASA in Austria, approached him to collaborate. Together, they developed the idea further, focusing on the potential for BECCS as a risk management tool in climate mitigation. This collaboration led to a published paper that introduced the concept of negative emissions, although BECCS was not named yet.

4. **2001: First Peer-Reviewed Paper (September)**
   Möllersten, Obersteiner, and a group of scientists published the paper *"Managing Climate Risk"* in *Science*. The paper highlighted how biomass energy combined with CCS could remove greenhouse gases (GHGs) from the atmosphere. It emphasised BECCS as a backstop technology to manage climate risk, especially if unforeseen climate feedbacks occurred. They argued that negative emissions could be achieved and potentially rewarded through systems like carbon credits, benefiting industries such as the pulp and paper sector.

5. **2000-2002: Parallel Development in the US**
   Around the same time, David Keith and James Rhodes at Carnegie Mellon University also began exploring the potential of combining bioenergy and CCS. By 2000, they had started discussions about biomass that implied negative emissions, and Rhodes focused on it for his PhD thesis. Their work paralleled the development of BECCS in Europe, and they continued to refine their analysis of bioenergy with CCS over the next few years.

6. **2005: Expansion in Climate Models**
   BECCS gained further prominence when climate scientists started including it in Integrated Assessment Models (IAMs) scenarios aimed at limiting global warming to below 2 degrees Celsius. Around 2005, BECCS began appearing in major climate scenarios, such as those used by the Intergovernmental Panel on Climate Change (IPCC), to show how negative emissions could help meet ambitious climate targets.

7. **Mid-2000s: Wider Recognition and Policy Consideration**
   As BECCS became more widely recognised, it was seen as a key negative emissions technology to help reduce global carbon levels. Scientists like Detlef van Vuuren worked on models that relied on BECCS to achieve stringent climate goals, and it started to be viewed as essential for meeting long-term targets like limiting warming to 2°C.

8. **2020 and Beyond: Crossroads for BECCS**
   By 2020, BECCS became a central part of climate mitigation discussions. However, there were growing concerns about the reliance on BECCS, its scalability, and whether decision-makers should depend on its future emergence or push for more immediate emission reductions. The debate around BECCS continues to focus on balancing near-term actions with potential future technologies.

Source: [16]

Current Global Implementation

United States

The United States is a global leader in BECCS deployment, with several active projects, particularly in bioethanol production and enhanced oil recovery (EOR). The Illinois Basin-Decatur Project (IBDP) captured up to 1 Mtpa (million tonnes per annum) of CO_2 between 2011 and 2014, from the fermentation process of corn at Archer Daniels Midland (ADM) ethanol plant in Decatur, Illinois [14]. This CO_2 is stored in a dedicated geological site known as Mt. Simon Sandstone, 2.13 km (7,000 feet) beneath the Illinois Basin [17].

IBDP referred to as "the most relevant" project to date by IPCC in 2014 [18]**.** However, Carbon Brief's study shows that the plant is not entirely carbon negative. Over 2.5 years, the facility emitted around 12.7 $MtCO_2$, and absorbed around 2 $MtCO_2$-eq, which means that the facility as a whole still emits around 10.6 $MtCO_2$-eq. By emitting more than it captures, the facility's overall emissions are not fully offset by the captured CO_2. Despite its limitations, this project marks the inaugural large-scale implementation of a technology that holds significant promise for future climate change mitigation efforts [18].

Several smaller initiatives in Kansas focus on EOR capturing CO_2 and bioethanol CCS. The Kansas Arkalon Bioethanol Plant CCS facility captures 200,000 tpa of CO_2 from corn fermentation, which is then compressed and transported via pipeline from an ethanol plant in Kansas to the Booker and Farnsworth Unit (FWU) Project in Ochiltree County, Texas, for EOR. This is seen as an interim step towards BECCS, while noting that more work is still needed, such as demonstrating sustainable biomass supply at scale [19].

In addition, the FWU Project captured anthropogenic CO_2 exhaust from the Agrium Fertilizer Plant in Borger, Texas. From both sources, the project captured nearly 800,000 Mt, with a total injection rate of approximately 0.2 Mtpa, from both sources. This CO_2 was piped to the Farnsworth Oil Field for EOR, although injection has since ceased as part of the DOE/NETL Southwest Partnership Development Phase. The injected CO_2 from this project continues to be monitored as part of ongoing EOR operations [20] [21].

Figure 2. The Illinois-Decatur BECCS Project: The World's Only Commercial-Scale BECCS Operation

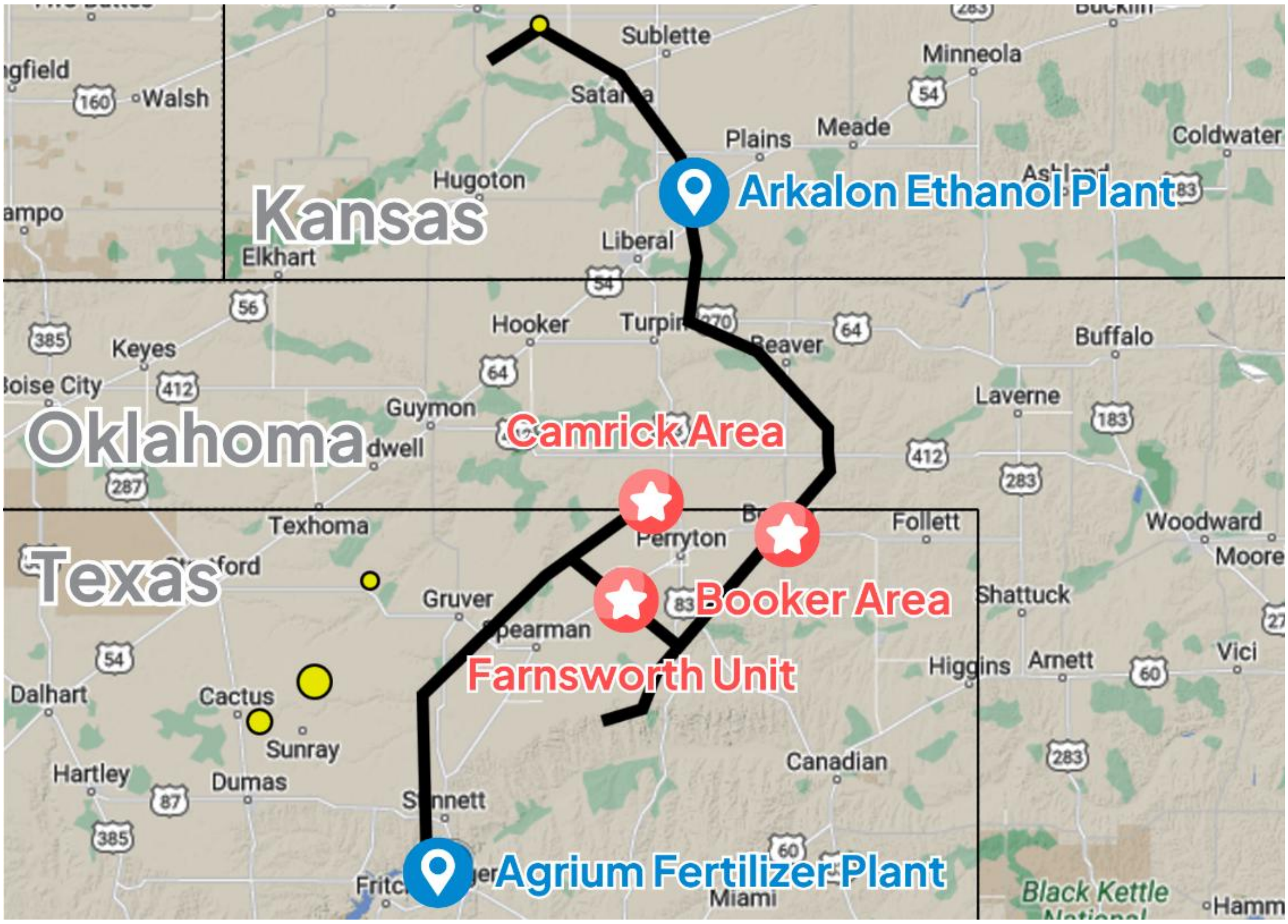
Source: Pemedia Network

The Bonanza Bioenergy Plant project, which has been in operation for more than a decade, captures 150,000 tpa of CO_2 from an ethanol plant processing corn and sorghum in Kansas and pipes it to the Stewart Oil Field, located 24 km (over 14 miles) from the plant, for EOR [21] [22].

Notably, the United States continues to innovate in BECCS. A new capture facility was recently commissioned at the Blue Flint Ethanol Plant near Underwood, North Dakota [23]. The Blue Flint CO_2 Project began injection in October 2023, capturing 100% of their CO_2 emissions and injecting approximately 600 MtCO_2 per day about one mile below the surface in the Broom Creek Formation [24].

To further support CDR technologies, the federal government has launched a CDR Purchase Pilot Prize, providing up to $35 million in cash awards in the form of offtake agreements from the federal government. This initiative aims to scale up carbon dioxide removal technologies, including BECCS as one of the pathways. The prize has awarded $1.2 million to 24 semi-finalists to develop their solutions. In the next phase, up to 10 teams will compete for $3 million each by producing a carbon dioxide removal credit purchase contract [25].

Figure 3. Arkalon Ethanol Plant and Agrium Fertilizer Plant interconnected to the Farnsworth Unit



Source: Redrawn from Balch et al.

Europe

Europe is making significant strides in BECCS development. In February 2024, the European Parliament and the Council of the EU reached a provisional agreement on the Carbon Removals and Carbon Farming Certification regulation (CRCF), which aims to standardise and certify carbon removal efforts across the region [23] [26]. BECCS and other biomass-based methods (BioCCS) are listed under permanent carbon removal activities that are covered by the regulation. However, BECCS projects will only qualify if the amount of CO_2 captured is greater than the CO_2 emissions associated with biomass production and project operation [27].

The first BECCS pilot project in Europe at Drax Power Station began in October 2018, capturing its first carbon in early 2019. It captured a tonne of CO_2 per day from the gases produced when renewable power is generated using biomass at the UK's biggest power station, near Selby in North Yorkshire [28]. A second pilot facility was installed by Mitsubishi Heavy Industries in autumn 2020, within Drax's CCUS Incubation Area. The pilot project will test MHI's carbon capture technology, and will capture around 300kg of CO_2 per day from biomass feedstock for the purpose of confirming its technology's suitability for use with biomass flue gases at Drax [29]. Drax is exploring options and locations to construct new BECCS plant globally, as well as planning to construct and install a BECCS unit in their own facility and achieve zero-carbon status in 2040 [30].

In Norway, the development of full-chain CCS projects is underway. The Klemetsrud CCS Project in Norway aims to capture 400,000 tonnes of CO_2 annually from the country's largest waste incinerator, with around 50% of the emissions being biogenic, potentially achieving 200,000 tonnes of negative emissions. It will be the world's first waste-to-energy (WtE) plant with full-scale CCS [31]. This project, part of Norway's Longship initiative, will utilise Shell's Cansolv technology and is expected to be operational by 2026/2027 [32].

The Norcem CCS Project involves CO_2 capture at the Norcem Brevik cement plant, also under the Longship project, with full funding secured. Both projects will use Equinor's Northern Lights JV for CO_2 transport and storage, marking significant steps toward large-scale carbon capture and storage in Norway. Both plants plan to send the captured CO_2 to a multi-user storage site in the Norwegian North Sea [33].

Figure 4. Drax Power Station

Source: Drax

In Denmark, the Danish Energy Agency (DEA) has established three subsidy funds to support CCS technology: the CCUS Fund, the Negative Emissions through Carbon Capture and Storage (NECCS) Fund, and the CCS Fund.

The NECCS Fund is specifically designed to support the capture and storage of biogenic CO_2, contributing to negative emissions. This fund operates with a support period of eight (8) years, which is significantly shorter than that of the CCUS Fund, which provides support for more than 20 years. The shorter support period for the NECCS Fund ensures that the cheapest biogenic sources are not locked into long-term storage, allowing them to be utilised for other purposes [34].

After postponing the deadline in November 2023, and adding an additional requirement from the EU Commission, the DEA finally awarded contracts on 17 April 2024, to BioCirc CO_2 ApS, Bioman ApS, and Carbon Capture Scotland Ltd. These projects will capture and store 160,350 tonnes of CO_2 annually from 2026 to 2032, concluding the NECCS Fund.

Japan

In Japan, the Mikawa Power Plant in Omuta City, Fukuoka, is in the planning stages for a BECCS retrofit. The plant aims to capture more than 600 tonnes of CO_2 per day, reducing its emissions by over 50%. Mikawa is a biomass-fired power plant that runs on palm kernel shell (PKS) as fuel. In 2020, Toshiba Energy Systems & Solutions Corporation constructed and began operating a CO_2 Capture Demonstration Plant as part of the Sustainable CCS Project, commissioned by the Ministry of the Environment, Government of Japan. This demonstration plant is fully integrated with the Mikawa Power Plant, connecting both the flue gas system and the steam cycle system. The captured CO_2 is planned to be transported and stored deep beneath the seabed offshore Japan in the future.

Additionally, a novel technology to mitigate amine emissions from the CO_2 capture plant has been developed and installed, with its performance under evaluation. Building on this CO_2 Capture Demonstration Plant, a series of facilities and ships will be constructed by 2030 to enable end-to-end verification from capture to storage [34][35].

Industry Applications and Integration

Biofuels Industry

The integration of CCS with bioethanol production is one of the most commercially attractive and technically mature applications of BECCS. As of 2017, bioethanol represented two-thirds of the 68 Mtoe of biomass-derived biofuels produced globally, with the United States leading this sector. Other regions, including South America, Sub-Saharan Africa, and Southeast Asia, present significant growth opportunities [33].

Bioethanol production is well-suited for CCS, because the process yields a near-pure CO_2 stream, minimising the cost and energy required for capture. One successful example is the Illinois Industrial CCS facility, which captures up to 1 Mtpa of CO_2 [33]. The captured CO_2 can be stored underground or utilised in other applications like EOR, potentially reducing the carbon footprint of bioethanol even further.

Energy Generation Industry

Biomass Power Plants

Biomass power generation represents about 52 Gigawatts (GW) of global capacity [33]**.** Integrating BECCS with these biomass power plants could contribute significantly to global emissions reduction efforts. A prominent example is the Drax Power Plant in Yorkshire, UK, which has transitioned from coal to biomass for three of its 660 MW units. Drax is also piloting a CO_2 capture facility which, if scaled up, can potentially become a key contributor to carbon-negative electricity [33].

Waste-to-Energy (WtE)

WtE involves incinerating municipal solid waste to generate heat and electricity. Incorporating carbon capture into WtE facilities allows the CO_2 from biogenic waste components to be captured, resulting in net negative emissions [33]. Countries with high waste incineration rates, such as Japan (burning 70% of its waste), Norway (53%), and several EU nations, are well-positioned to integrate BECCS into their WtE systems. The European Union operates 455 WtE facilities, while China and the USA host 223 and 74 plants, respectively [33]. Capturing CO_2 from these plants can contribute to global emissions reduction efforts, leveraging technology similar to that used in fossil fuel plants..

Power-to-X (PtX)

PtX are emerging technologies that convert captured CO_2 into synthetic fuels, chemicals, and materials like plastics. These processes rely on hydrogen, typically produced through electrolysis using renewable energy. By combining hydrogen with CO_2, these technologies can create energy-dense fuels or valuable products like synthetic natural gas, methanol, or even jet fuel [36].

CO_2 for PtX can be sourced from bioenergy plants, direct air capture, or industrial processes such as cement production. Bioenergy facilities are particularly suited for this, especially large biomass co-firing plants, as they often produce pure CO_2 streams, reducing purification costs [36].

Heavy Industries

The cement industry is one of the hardest-to-decarbonise sectors, primarily due to its high heat and energy demands. Globally, biomass currently provides around 6% of the thermal energy used in cement production. However, cement manufacturing also emits significant amounts of CO_2, which makes CCS the most viable option for decarbonisation.

Norway's Norcem cement plant is a notable example, co-firing up to 30% biomass and planning to capture up to 400,000 tonnes of CO_2 annually through a BECCS facility [33]. The global cement industry has set a target of reducing emissions by 20% to 25% by 2030, and BECCS will be critical to achieving this goal, contributing to emissions reduction while meeting the sector's energy needs [33].

Opportunity for ASEAN Countries

Natural Resources and Power Potentials

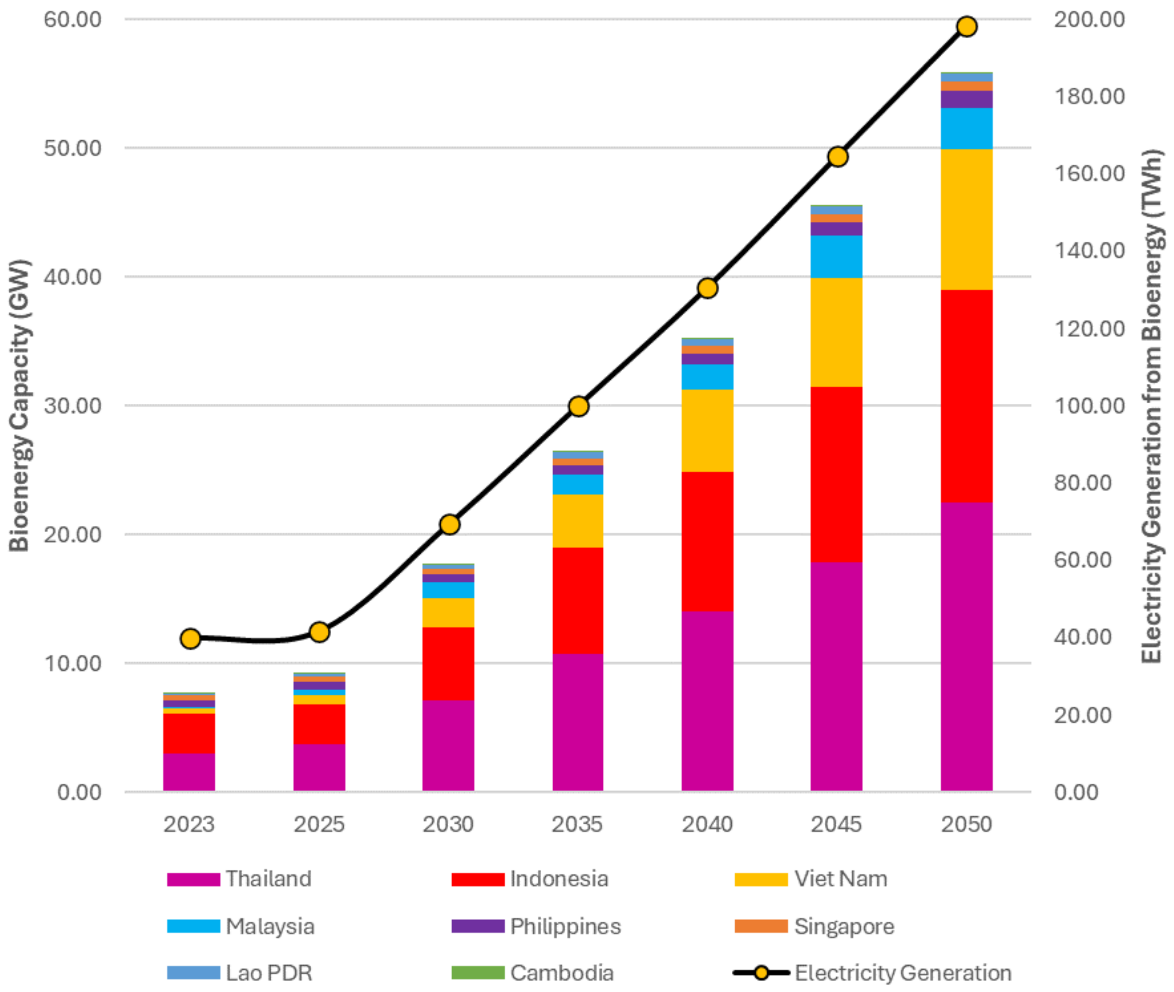
ASEAN countries possess immense potential in bioenergy and BECCS technologies, offering a pathway toward more sustainable energy systems. The region's vast biomass resources, such as agricultural residues and forestry by-products, provide the foundation for bioenergy development. This transition can help diversify the region's energy source mix, while enhancing energy security.

According to the AEO8, Southeast Asia could reach 55.34 GW of energy capacity from bioenergy according to the baseline scenario, and might exceed 100 GW according to the carbon-neutral scenario [37].

Another source also mentions the greenhouse gas emissions reduction from utilising bioenergy might reach approximately 442 Mt-CO_2e [38]. Additionally, the AEO8 projects that ASEAN could meet 10% to 22% of its energy demand from bioenergy by 2050 [37].

This is a significant rise in bioenergy use across ASEAN, with Indonesia, Thailand, and Viet Nam emerging as the major contributors to this growth starting from 2030. Despite starting with a significantly lower share, Malaysia demonstrates commendable growth in bioenergy capacity for electricity generation.

Figure 5. Energy Capacity and Electricity Generation from Bioenergy in ASEAN (Baseline Scenario)



Source: The 8th ASEAN Energy Outlook

The region's suitability for bioenergy development is deeply rooted in its diverse landscapes, from Indonesia's and Malaysia's palm oil plantations, to Thailand's rice paddies.

As the world's largest producer of palm oil, Indonesia has made significant investments in bioenergy, particularly by expanding its biodiesel programme, with a target of 40% palm oil blending (B40) in the near future.

Malaysia has followed suit, with similar biodiesel initiatives and has also integrated palm oil waste biomass into energy production.

Thailand, a regional leader in biomass energy, utilises rice husks and sugarcane bagasse for electricity and fuel generation, positioning itself as a key player in Southeast Asia's renewable energy transition.

Viet Nam, with its abundant agricultural residues, particularly from rice production, has also made significant strides in bioenergy. The country is leveraging biomass and biogas technologies to reduce its dependence on fossil fuels, making bioenergy the largest renewable energy source, with a primary supply of 95.28 TWh in 2018 [39].

Additionally, the Philippines is harnessing its coconut industry for biofuels, while Lao PDR and Cambodia are exploring bioenergy opportunities from forestry and agricultural residues [40] [41] [42].

This synergy of bioenergy and BECCS not only supports ASEAN's climate goals, but also sparks wider economic opportunities. Investments in BECCS could lead to sustainable infrastructure, drive innovation, and create new job opportunities, especially in rural areas where biomass is abundant.

However, realising this potential requires more than resources—it demands coordination between policymakers, investors, and technology developers. The integration of bioenergy and BECCS will need strategic efforts to overcome technological and regulatory hurdles, but its promise of a greener, energy-secure future for ASEAN is both achievable and transformative [42][43].

Table 1. Bioenergy Potential and Installed Capacity in AMS

Country	Bioenergy Potential	Installed Capacity (per 2022)
Brunei Darussalam	278 MW (annual potential)	N/A
Cambodia	1,000 MW	28.6 MW
Indonesia	50,000 MW	3,098.9 MW
Lao PDR	300 MW	43 MW
Malaysia	29,000 MW	71.7 MW
Myanmar	11,640 MW	N/A
Philippines	2,500 MW	611 MW
Singapore	92.34 MW (annual potential)	393 MW
Thailand	7,190 MW	2,692.4 MW
Viet Nam	300,000 MW	395 MW

Sources: ASEAN Power Updates 2023, International Energy Agency (IEA)

The ASEAN region demonstrates significant potential for bioenergy development, with substantial disparities in both bioenergy potential and installed capacity across Member States, as depicted in Table 1.

Viet Nam leads the region in bioenergy potential, with an estimated 300,000 MW, yet its installed capacity stands at 395 MW, indicating considerable untapped opportunities. Similarly, Indonesia, with a bioenergy potential of 50,000 MW, has achieved an installed capacity of 3,098.9 MW, showcasing progress yet leaving room for further development. Malaysia boasts a potential of 29,000 MW, but has only utilised 71.7 MW, while Thailand has made notable strides with an installed capacity of 2,692.4 MW against a potential of 7,190 MW.

Smaller nations reveal interesting dynamics. Cambodia, with 1,000 MW of potential, has installed 28.6 MW, and the Lao PDR shows progress with 43 MW of installed capacity out of a 300 MW potential. Myanmar, despite a potential of 11,640 MW, has not yet reported installed capacity figures. Brunei Darussalam and Singapore, with annual potentials of 278 MW and 92.34 MW respectively, present contrasting progress; Brunei's installed capacity is unreported, whereas Singapore has reached 393 MW. The Philippines stands out with a balanced trajectory, achieving an installed capacity of 611 MW, out of a 2,500 MW potential, demonstrating ongoing efforts to harness bioenergy. The Philippines stands out with a balanced trajectory, achieving an installed capacity of 611 MW out of a 2,500 MW potential, demonstrating ongoing efforts to harness bioenergy.

These figures picture the need for ASEAN nations to focus on scaling bioenergy technologies, investing in infrastructure, and adopting supportive policies to close the gap between potential and realisation, which in this report, focusing through biomass utilisation is mainstreamed.

In terms of biomass, the region has abundant resources, with each country leveraging its unique agricultural and forestry materials to harness significant bioenergy potential. ASEAN's agricultural and forestry sectors have an estimated annual biomass potential exceeding 500 million tonnes, which equates to over 2,200 TWh each year [44]. From Brunei Darussalam to Viet Nam, nations across the region are tapping into their abundant biomass supplies to drive renewable energy development and reduce dependence on traditional energy sources. The diverse availability of biomass resources, tailored to the specific agricultural and industrial strengths of each country, underscores the region's immense capacity for sustainable energy production, and highlights the critical role of biomass in Southeast Asia's energy transition.

Brunei Darussalam

Brunei Darussalam, a nation rich in oil and gas resources, has historically relied heavily on fossil fuels to secure its national energy needs and support its economic growth. However, recognising the global shift towards renewable energy and the necessity to diversify its energy portfolio, Brunei Darussalam has set an ambitious goal of achieving 10% of its electricity from renewable sources by 2035.

As of 2023, Brunei Darussalam has not developed significant bioenergy capacity, with reports indicating 0 MW of installed capacity, despite an annual bioenergy potential of 278 MW. The country has focused primarily on fossil fuels, particularly oil and gas, which dominate its energy landscape [45]. Nevertheless, the country's biomass resources are relatively modest, but include valuable materials such as coconut shells, coconut fibres, corn fibres, rice husks, and sawdust. While Brunei Darussalam's focus has primarily been on fossil fuels, these biomass resources present an emerging opportunity for integrating renewable energy solutions in the country's energy mix.

Cambodia

Cambodia's Cambodia's extensive forest coverage, which spans 57% of the country's total land area, provides a significant biomass resource. Wood and wood charcoal play a crucial role in the nation's energy consumption, making up approximately 80% of total energy use. In urban areas, these sources account for around 80% of energy needs, while in rural areas, dependence is even higher, at 94%.

Beyond forest resources, agricultural residues—including rice husks, rice straw, corn cobs, cassava stalks, bagasse, groundnut shells, and coconut shells—also contribute significantly to the biomass supply. As of 2019, Cambodia's installed biomass capacity stood at 28.6 MW, with an estimated untapped potential of around 1,000 MW (97% of total potential biomass energy) [46].

A notable development in Cambodia's biomass sector is Heineken's biomass power plant, built in 2021, which stands as the largest biomass power plant in the country. This facility utilises rice husks from the nearby Prey Vang province to generate electricity for its brewery operations, adding more than 9 MW of installed capacity to the country's electricity grid [47].

Although the Heineken project does not currently incorporate CCS technology, it demonstrates the potential for biomass energy in the country and could be adapted for BECCS in the future. Heineken's initiative is part of a broader effort to reduce CO_2 emissions from production, with the company aiming for a 60% reduction in emissions by switching to biomass. This transition is expected to save approximately 17,000 tonnes of CO_2 annually [48]. This contributes not only to the company's net-zero target by 2030, but also to Cambodia's SDGs, particularly Goal 7, which focuses on ensuring access to affordable, reliable, and sustainable energy.

Indonesia

Indonesia, with its vast forest cover spanning approximately 94,432,000 hectares, is one of the most prominent sources of biomass in Southeast Asia. The country's agricultural sector further contributes to its biomass resources, providing materials such as oil palm and sugarcane residue, rice husks and straw, and corn cobs. Indonesia's annual biomass production is estimated at 146.7 million tonnes.

Indonesia's biomass energy potential is substantial, with an estimated capacity of about 32,600 MW. In 2020, 46.59 TWh of electricity from bioenergy was generated in the country [46]**. Indonesia has launched a new collaborative initiative to assess the feasibility of BECCS.** The project is a partnership between Japan's Marubeni Corporation and Japan Petroleum Exploration Co., Ltd. (JAPEX), along with Indonesia's state-owned energy company, PT Pertamina, and its subsidiary PT Pertamina Hulu Energi (PHE).

The study focuses on capturing CO_2 emissions from biomass-fuelled boilers used for self-power generation at the PT Tanjungenim Lestari Pulp and Paper (TEL) mill, a Marubeni subsidiary. The captured CO_2 would then be injected and stored in synclinal aquifers in the northern Limau oil field, managed by Pertamina, near the TEL facility. The project aims to begin operations by 2030 [49].

In conjunction with this initiative, researchers have conducted detailed evaluations of various biomass types to assess the cost and efficiency of BECCS in Indonesia. Using computer models, six types of biomass—bagasse, palm kernel shell, rice straw, empty fruit bunch, and refuse-derived fuel—were analysed. The findings revealed that BECCS is most effective in large plants (over 20 MW) with high CO_2 concentrations (above 12.1%), while biomass with low energy content (less than 23.14 MJ/kg) is unsuitable. Of the six biomass types assessed, palm kernel shell and rice straw were identified as the most viable for BECCS implementation in the region [50].

Lao PDR

Lao PDR benefits from considerable forest resources, with approximately 68% of the country covered by forests. This extensive forest area contributes to the biomass supply, which is crucial for rural households, with 80% of the population relying on firewood and charcoal for their energy needs. Biomass from the agricultural sector also adds to the energy mix. Presently, Lao PDR has a biomass energy potential of 938 MW. However, no significant initiatives have been undertaken to harness this capacity [46].

Malaysia

Malaysia, with its extensive forest coverage accounting for about 62% of the country's land area, and significant agricultural activities, has substantial biomass resources. Key sources include oil palm, sugarcane, and coconut residues. The palm oil industry, a major contributor to Malaysia's gross national income, generates considerable biomass, with estimates indicating production of around 83 million dry tonnes in 2012, potentially rising to 100 million dry tonnes. The total biomass capacity potential in Malaysia is estimated at 2,300 MW. This highlights Malaysia's significant role in the biomass energy sector and its potential for further expansion [46].

Malaysia's National Biomass Action Plan supports this potential by highlighting Malaysia's vast biomass resources. In 2022, the country was estimated to have a biomass potential of 182.6 million tonnes per year, with 85.17% derived from the oil palm biomass industry. As of 2019, Malaysia had achieved a total installed capacity of 440.5 MW of biomass-powered energy, including 70.65 MW from grid-connected power plants. This accounted for 1.2% of the nation's total electricity generation, contributing to a reduction of 395.22 Gg CO_2-equivalent emissions [51].

In Malaysia, BECCS is being explored as a potential solution to reduce carbon emissions by utilising palm oil waste, a major byproduct of the country's palm oil industry. As the world's second-largest producer of palm oil, Malaysia dedicates 5.7 million hectares to palm oil plantations, generating around 65 million tonnes of waste annually. This includes fronds, trunks, empty fruit bunches (EFBs), shells, and fibres. While some of this waste is already used for energy production, a significant portion remains unutilised, often ending up in landfills or decomposing in fields.

Studies suggest that BECCS could enable substantial carbon dioxide removal, capturing between 840 kg and 1,729 kg of CO_2 per tonne processed. However, its implementation also increases other environmental impacts by 13% to 217%, compared to systems without CCS. Economically, BECCS presents challenges, as it is significantly more expensive. The levelised cost of electricity (LCOE) is 3.6 to 4.1 times higher, ranging from \$98 to \$119 per MWh. Despite these hurdles, BECCS has the potential to reduce emissions from Malaysia's electricity sector by 10%, and increase the share of bioenergy in the national energy mix by 7.6 times [52].

Myanmar

Myanmar, an agricultural nation with substantial forest cover, relies heavily on biomass for its energy needs. The country produces over 20 million tonnes of rice paddy annually, contributing to its rich biomass resources. Biomass from both forest and agricultural sectors constitutes around 65% of Myanmar's total energy consumption. The combined capacity potential from biomass in Myanmar is 6,900 MW, with an installed capacity of 115 MW in 2019 [46].

Philippines

Biomass provides nearly 30% of the energy used by the country's 100 million inhabitants, with a significant portion dedicated to household cooking in rural areas. The biomass sector is rapidly advancing, supporting the energy sector with a potential capacity of 210 MW. Biomass energy accounts for approximately 15% of the Philippines' primary energy use, reflecting its growing importance in the nation's energy strategy [46].

Although direct combustion remains the primary method of bioenergy power generation in the Philippines, there is growing interest in alternative technologies, such as biomass gasification, which could open up new opportunities for more efficient energy production and carbon capture. For instance, the Centre for Rice Husk Energy Technology in the Philippines has developed a moving-bed downdraft rice husk gasifier that allows for continuous operation in a single reactor [53] [54]. By coupling gas conditioning equipment to the gasifier reactor, clean gas is derived from the rice husks, which can be used as fuel for an internal combustion engine.

Singapore

Singapore, a city-state with limited land area and minimal forest cover, has nonetheless made strides in biomass energy. The nation has invested significantly in clean technology, with S$700 million allocated to research, innovation, and development in this sector. Biomass energy in Singapore is derived mainly from horticultural and wood wastes. The current biomass energy potential is about 92.34 MW annually. Singapore's efforts in biomass utilisation, though modest compared to larger countries, contribute to its overall clean energy goals [46].

In addition to its biomass initiatives, Singapore has advanced significantly in the application of WtE technology. At present, the country operates four WtE plants, with a fifth plant in Tuas slated to be operational in 2021, and one off-shore disposal site at Semakau Landfill. The WtE plants play a crucial role in Singapore's waste management system, reducing waste volume by up to 90% through incineration, which in turn saves valuable landfill space. Moreover, the WtE process not only addresses waste disposal challenges, but also contributes to the nation's energy mix. Heat from the incineration process is recovered to produce steam, which propels turbine-generators to produce electricity, meeting up to 3% of Singapore's total power needs [55].

Recognising the challenges associated with adopting carbon capture, utilisation, and storage (CCUS), Singapore's Energy Market Authority (EMA) is taking proactive steps to address these obstacles. In collaboration with industry partners and the research community, EMA is exploring pilot projects and research initiatives aimed at overcoming the barriers to CCUS implementation. To support these efforts, the EMA launched the Low Carbon Energy Research Funding Initiative in 2021, which focuses on advancing technologies such as hydrogen and CCUS to aid in the decarbonisation of Singapore’s power and industrial sectors [56].

Thailand

Biomass can meet up to 20% of the country's energy demand, with an estimated capacity potential of 18,000 MW. The country has a robust biomass energy infrastructure, including large-scale, centralised facilities. In 2019, Thailand's installed capacity for biomass stood at 1,610 MW.

Thailand’s government support, including tax incentives and import duty exemptions, further encourages the development of biomass energy projects [46]. Governmental support in power generation using renewable energy is primarily in the form of regulatory policies, such as a Feed-in Tarriff.

In Thailand, a study assessed the potential of various Negative Emissions Technologies (NETs), including BECCS, using a Geographic Information System (GIS) analysis to evaluate land availability and carbon removal potential. The study found that BECCS could be implemented on 24,236 km² of marginal land not currently used for agriculture or other significant purposes. Under a more aggressive, intensive land-use scenario, BECCS could expand to 109,222 km², encompassing areas that would require more intensive management and land conversion. The estimated carbon removal potential ranges from 8.44 Mt to 33.78 Mt of CO_2-equivalent per year in the marginal land scenario, and from 32.04 Mt to 128.18 Mt CO_2-equivalent per year in the intensive scenario [57].

Furthermore, the study suggested that BECCS could be combined with other NETs, such as Afforestation and Reforestation (AR) and Biochar production, to maximise the efficiency of land use and carbon removal. This integration could not only enhance biodiversity and improve soil health, but also increase the overall effectiveness of carbon sequestration efforts in Thailand [57].

Viet Nam

Viet Nam, with its extensive agricultural activities, has abundant biomass resources, contributing to a theoretical capacity potential of over 7 GW. Biomass is predominantly used in households, making up 76% of total energy consumption, with the remainder used in small industrial applications and combined heat and power plants. Major biomass sources include forest residues, rice husks and straw, bagasse, cane trash, maize trash, cassava stems, peanut shells, coffee husks, and coconut shells. Viet Nam has set a target to achieve a combined biomass power capacity of 2,270 MW by 2030, aiming to expand this to 6,015 MW by 2050, reflecting its commitment to enhancing biomass energy utilisation [46].

Table 2. Biomass Resource Potential in AMS

Country	Annual Biomass Production	Biomass Energy Potential	Key Biomass Resources
Brunei Darussalam	N/A	278 MW (annually)	Coconut shells, coconut and corn fibers, rice husks, sawdust
Cambodia	N/A	1,000 MW	Rubber, rice, maize, cassava stalk, sugarcane, groundnut, coconut, jatropha, oil palm
Indonesia	146.7 million tons	32,600 MW	Palm oil and sugarcane residues, rice husks and straw, corn cobs
Lao PDR	N/A	938 MW	Firewood, charcoal, agricultural residues
Malaysia	100 million dry tons	2,300 MW	Palm oil, sugarcane and coconut residues
Myanmar	20 million tons	6,900 MW	Paddy residues, firewood, agricultural residues
Philippines	N/A	210 MW	Agricultural residues, bagasse, rice husks, coconut shells
Singapore	N/A	92.34 MW (annually)	Horticultural waste, wood waste
Thailand	N/A	18,000 MW	Rice husks, bagasse, corn cobs, palm kernell shell
Viet Nam	N/A	7,000 MW	Rice husks and straw, forest residues, cassava

Source: [46], ACE internal RE Database

Classifying Biomass Co-Firing with CCS as Part of BECCS

The integration of biomass co-firing with CCS has emerged as an important strategy in the transition towards sustainable energy systems. While some recent literature, such as the works of Weimann and Bentsen, and Rahmanta, et al., have refrained from explicitly categorising this practice as BECCS, a broader examination of the definitions and applications of BECCS reveals that biomass co-firing within conventional coal-fired power plants (CFPPs) should indeed be considered part of this practice [58][59].

BECCS is characterised by the combination of biomass energy production with the capture and storage of CO_2 emissions. This process inherently involves the combustion of biomass, which is considered carbon-neutral over its lifecycle, due to the CO_2 absorbed by the biomass during its growth phase. By integrating CCS technology, the CO_2 released during combustion can be captured and stored underground, effectively removing it from the atmosphere and contributing to negative emissions [58][59].

The scope of BECCS is not limited to specific types of biomass or configurations for power generation. Rather, it encompasses a range of methodologies aimed at reducing atmospheric CO_2. This flexibility is essential, as different geographical and technological contexts necessitate diverse approaches to carbon management. Therefore, while Weimann and Bentsen, as well as Rahmanta, et al., may not classify biomass co-firing with CCS as BECCS, the fundamental principles underpinning BECCS are indeed applicable to this practice [58][59].

In examining the literature, it becomes evident that biomass co-firing represents a viable method for achieving substantial emission reductions in traditional coal-fired power plants. For instance, the study by Weihs, et al., argues for the inclusion of biomass co-firing with CCS as a forward-looking strategy for coal-dependent regions, illustrating the environmental benefits of this approach despite some noted increases in other impact categories. This perspective aligns with the overarching goals of BECCS, which aims to mitigate greenhouse gas emissions, while transitioning energy systems toward lower carbon alternatives [60].

Furthermore, Yang et al., emphasise the efficacy of co-firing biomass with coal in enhancing decarbonisation efforts, categorising this practice within the framework of BECCS. This position is reinforced by empirical evidence demonstrating that strategic co-firing ratios can significantly lower carbon emissions and enhance the sustainability of energy production [61].

Some researchers may be reluctant to classify biomass co-firing with CCS as BECCS due to a narrow interpretation of the term. However, the core principle of BECCS is not defined by the specific configuration of the power generation system, but by its ultimate goal—the reduction of atmospheric CO_2.

As highlighted by Jones, et al., biomass co-firing with properly implemented CCS can achieve negative emissions, thereby fulfilling a key objective of BECCS [62]**.** Similarly, Wang, et al. further emphasise the potential of biomass co-firing in coal-fired power plants (CFPPs), noting that substantial biomass ratios are required to reach carbon neutrality [63]. This perspective underscores the flexibility of BECCS across different energy systems, reinforcing the argument that biomass co-firing should be recognised as part of the BECCS framework.

Therefore, the scientific basis for considering biomass co-firing with CCS as part of BECCS is well-founded. Despite differing interpretations in recent literature, the fundamental principles of BECCS encompass a wide range of practices aimed at carbon reduction. The integration of biomass co-firing within conventional coal-fired power plants presents a promising pathway for achieving significant emission reductions and advancing towards net-zero targets. As energy systems evolve, it is crucial for policymakers and researchers alike to recognise the potential of biomass co-firing as an integral component of BECCS, ensuring that it maximises the efficacy of carbon management strategies in the pursuit of a sustainable future.

Infrastructure Integration Readiness

The integration of biomass co-firing in CFPPs across ASEAN is gaining momentum as countries work to reduce carbon emissions and diversify their energy mix.

A key example is the Malakoff biomass co-firing initiative at the Tanjung Bin Power Plant (TBPP) in Johor, Malaysia, which marks a significant step in this transition. Operated by Malakoff Corporation, TBPP has set ambitious targets to cut carbon emissions by 45% by 2030, and to increase the share of renewables in its energy mix from 40% to 70% by 2050 [64]. The plant launched its pilot trials in December 2022, initially implementing a biomass co-firing ratio of 0.5%. Since then, this ratio has increased to 2%, with plans to reach 3% by 2025.

According to the National Energy Transition Roadmap (NETR), this pilot phase will help scale up biomass co-firing to a minimum of 15% by 2027 [65]. The primary biomass fuel used in the pilot phase consists of empty fruit bunch (EFB) pellets, while ongoing assessments are exploring the feasibility of wood chip pellets, rice husk pellets, and palm kernel shells as alternative fuel sources [66].

In Thailand, the Mae Moh Power Plant (MMPP), managed by the Electricity Generation Authority of Thailand (EGAT), is making strides in biomass co-firing. A Memorandum of Understanding with Japan’s IHI Corporation has facilitated testing of wood pellets in one of its 300 MW units, achieving a co-firing ratio of 2%, as of March 2024. EGAT has ambitious plans to increase this ratio to 5%, and eventually 15% in the coming years, with an estimated requirement of 200,000 tonnes of wood pellets annually to support the largest target. Encouragingly, Thailand’s domestic production of wood pellets is projected to meet this demand, with an estimated annual output of around 600,000 tonnes [67] [68].

Singapore's Tembusu Multi-Utilities Complex (TMUC) at Jurong Island, operated by Tuas Power, showcases another model of biomass co-firing. The plant was initially designed to operate with an 80:20 ratio of coal to biomass, but has successfully adjusted its operational ratio to 70:30. This flexibility indicates a growing acceptance and implementation of biomass as a viable complement to traditional coal use [69].

Indonesia is actively pursuing biomass co-firing as part of its National Electricity General Plan. In 2021, the state-owned electricity company PLN conducted trials across 26 CFPPs, incorporating biomass ratios of 1% to 5%. By 2024, the total capacity for biomass co-firing is expected to reach an impressive 18 GW, with 13 units already in commercial operation across Java, Borneo, Sulawesi, and Lombok. These operations utilise a variety of biomass feedstocks, including sawdust, non-toxic and hazardous waste, palm shells, rice husks, and wood pellets, reflecting the diverse agricultural landscape of Indonesia [70].

The integration of CCS technology into CFPP with biomass co-firing offers a viable pathway for significant emission reductions in Southeast Asia, exemplified by projects in Malaysia and Indonesia.

In Malaysia, for instance, implementing CCS in the Tanjung Bin Power Plant (TBPP), already running on biomass co-firing, could cut emissions by up to 60%, underscoring the environmental benefits of such retrofits [71]. Similarly, Indonesia is advancing its clean energy agenda with the strategic placement of most CFPPs with biomass co-firing on Java, along with plans for 16 CCS/CCUS projects set to commence operations by 2030 [72]. These efforts highlight the region’s commitment to decarbonisation, yet further research and development are crucial to ensure that CCS integration with biomass co-firing is economically sustainable and technologically effective, maximising its potential to transform CFPPs into more environmentally responsible energy sources.

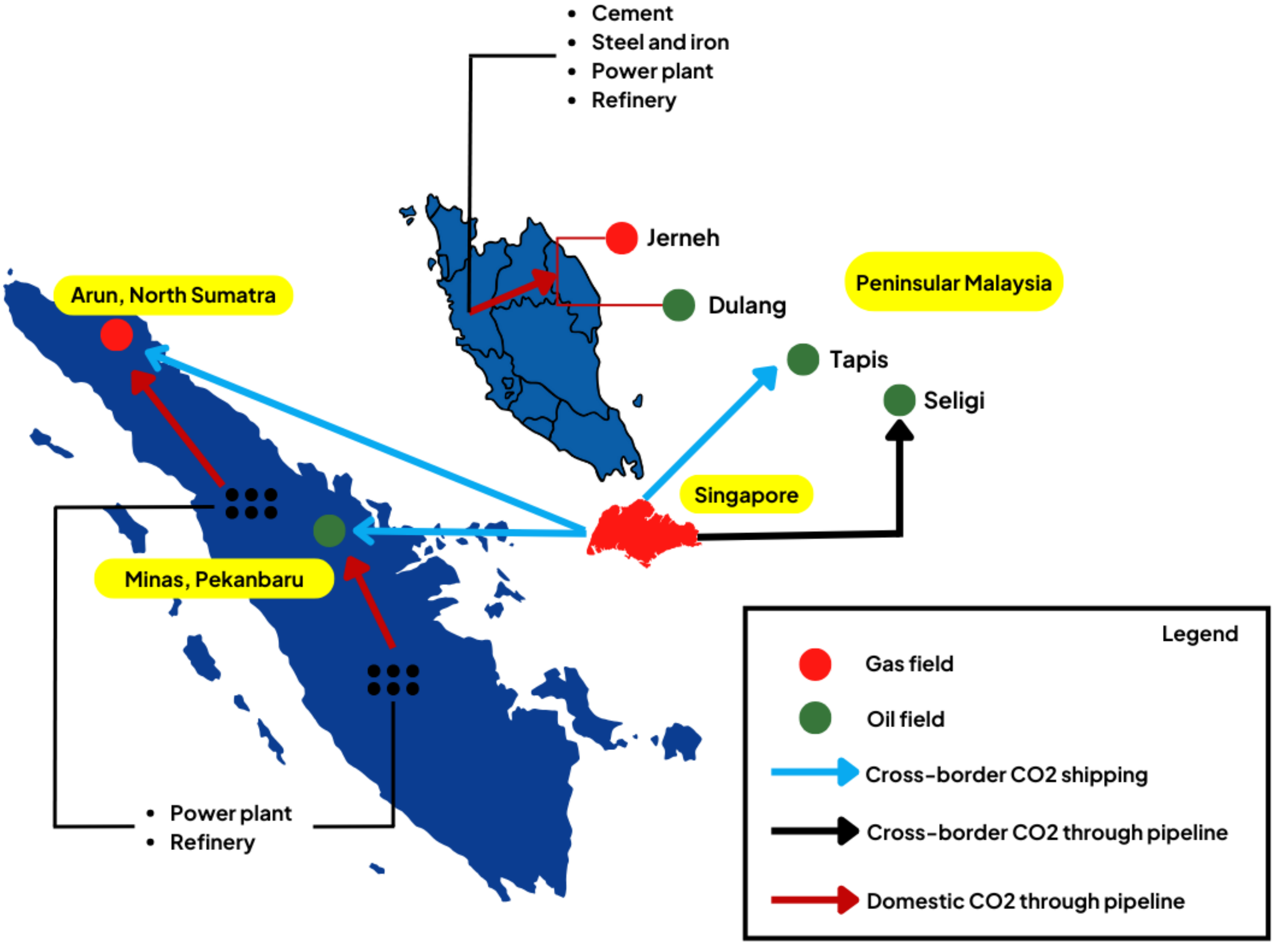
Regional CO_2 Transport Networks

CO_2 emissions originate from multiple key industries, each contributing significantly to global emissions. The cement industry is a major emitter, releasing large quantities of CO_2 during the calcination process, a key step in cement production. Likewise, the steel and iron industry generates substantial emissions due to its reliance on fossil fuels and the chemical reactions involved in metal production. Power plants, especially those that burn fossil fuels, are another major source of CO_2 emissions. Additionally, oil refineries, which process crude oil, release significant emissions as a by-product of their operations [73].

As shown in Figure 6**, a comprehensive case study identifies six potential CO_2 storage sites for the permanent sequestration of emissions.** These sites are strategically located within existing oil and gas operational areas, including Arun in Northern Sumatra, Minas in Riau Province, and several locations in Peninsular Malaysia—Jerneh, Dulang, Tapis, and Seligi. These locations provide viable storage solutions, ensuring that captured CO_2 is effectively and sustainably managed.

Additionally, Singapore has been proposed as a central hub for CO_2 transport, serving as the starting point for emissions to be transferred to these storage sites. Its strategic location could enable cross-border CO_2 transport, optimising logistics and enhancing the efficiency of regional carbon management efforts.

Figure 6. Potential CO_2 Transport in ASEAN



Source: Zhang & Lau, 2022

Geological Storage Prospects

Geological storage of CO_2 in the ASEAN region appears promising. Research conducted by the National University of Singapore (NUS) highlights several key findings that underscore the region's capacity for effective CO_2 storage [68]. The total stationary CO_2 emissions from various industrial sources, including power plants, iron and steel mills, cement factories, and refineries, amount to approximately 391 million tonnes per annum (Mtpa). Notably, power plants contribute the largest share, accounting for 51% of these emissions, followed by iron and steel mills at 24%, cement factories at 15%, and refineries at 10% [74].

In terms of storage capacity, the study indicates that there are an estimated 386 gigatonnes (Gt) of mid-range CO_2 storage resources within the same area, which is sufficient to accommodate nearly 987 years of emissions from stationary sources. A significant portion of this capacity—379 Gt, or 98%-- is located within saline aquifers, while 6.2 Gt can be found in gas reservoirs and 0.5 Gt in oil reservoirs [74].

The potential for enhanced oil recovery (CO_2-EOR) in the region's oil reservoirs is significant, with an estimated 1,857 million barrels (MMbbl) of recoverable oil identified. Key oil fields, including the Minas oilfield in the Central Sumatra Basin and the Seligi and Dulang fields in the Malay Basin, exhibit the highest CO_2-EOR potential.

Additionally, CO_2-enhanced gas recovery (EGR) presents an opportunity to recover an extra 163 MMbbl of condensate, with the Arun gas condensate field in the North Sumatra Basin showing the greatest potential.

While many oil fields in the region are ready for CO_2-EOR, several gas fields remain in the primary depletion stage, making them unsuitable for CO_2 storage at this time [74].

Challenges in ASEAN Countries

The successful deployment of BECCS in the ASEAN region faces several critical challenges that must be addressed.

One key issue is the availability of land and biomass, as suitable areas must be allocated without compromising food security or biodiversity. Additionally, the technological and economic feasibility of BECCS projects varies across member countries, depending on local infrastructure and investment capacity. This variation is particularly important given the need to assess both environmental and social impacts, as large-scale biomass cultivation can significantly affect local communities and ecosystems.

Another major challenge is carbon storage capacity and infrastructure. Effective BECCS deployment requires secure storage sites and well-developed facilities, yet many ASEAN countries may lack the necessary infrastructure to support large-scale carbon capture and storage. Addressing these interconnected challenges is essential for the successful integration of BECCS into the ASEAN energy transition strategy.

Resource Availability and Land Use

Land Use: BECCS requires vast amounts of land for biomass cultivation, which can compete with food production and biodiversity conservation. Globally, meeting the biomass supply needed for a CO_2 concentration pathway aligned with the 2°C target would require an additional 300 million to 600 million hectares of land for energy crops.

This area is comparable in size to the European Union and represents approximately 40% of the world's arable land. To minimise the impact on existing croplands, this land is expected to come from abandoned agricultural fields and natural grasslands. However, the uneven distribution of biomass resources may also drive global trade, with developed nations potentially relying on biomass imports from less developed regions.

In ASEAN, where agriculture is vital to both food security and economic stability, competition for land is particularly intense. Countries such as Indonesia, Thailand, and Malaysia have extensive arable land, but allocating significant portions to energy crops could worsen food security concerns. The region is already facing environmental degradation from palm oil plantations, which have reduced the availability of land for food crops.

With a growing population and increasing food demand, shifting land use from food production to energy crops could lead to higher food prices and reduced food availability, exacerbating existing food security challenges [75].

Sustainable Biomass Supply: Ensuring a sustainable and consistent biomass supply for BECCS presents significant challenges, particularly given the varying availability of resources across different regions.

Biomass can be sourced from agricultural residues, forestry by-products, or energy crops, but securing a reliable feedstock is difficult in areas where land is already in high demand for food production or biodiversity conservation. Competing land uses may limit biomass availability, especially in densely populated regions or those with extensive agricultural activity.

Additionally, large-scale bioenergy operations that rely on fast-growing biomass can produce emissions comparable to those from fossil fuels, undermining the carbon neutrality of bioenergy. To address these challenges, it is essential to explore different scenarios for biomass utilisation, whether as a standalone energy source or in combination with other renewable resources.

The future potential of biomass energy in reducing CO_2 emissions, particularly in Southeast Asia, is supported by various projections. One scenario suggests that by 2050, direct combustion technology for biomass will be adopted at different rates across regions, with 23% in China, 17% in India, 14% in the US, and 13% in Southeast Asia.

Notably, Southeast Asia, despite historically relying on fossil fuels, is expected to achieve relatively good biomass development by 2050, especially when compared to its current application in the region, which remains under 1%.

This promising outlook is reinforced by the substantial potential for BECCS in Southeast Asia. Several industrial-scale BECCS applications could be viable in the region. One prominent option is woody biomass combustion, which is already being piloted or even commercially implemented in some ASEAN coal-fired power plants that co-fire with biomass.

Other viable BECCS approaches include bioethanol fermentation, biomass gasification for biofuel production, and biogas generation through anaerobic digestion. Additionally, waste-to-energy (WtE)-based BECCS presents another opportunity, where WtE combustion or landfill gas (LG) combustion could be integrated with carbon capture technology to further reduce emissions.

Table 3. BECCS Application Potential in Various Industries

Industries	Required Biomass Resources	CO_2 Capture Potential	Possible Industry Application	Geographic Suitability in ASEAN
Biofuels Industries	Agricultural residues (e.g., corn, sugarcane)	Bioethanol: very high CO_2 concentration (near pure stream, 98-99%) [4]	Capturing and storing carbon from biofuels industries emission	Countries with strong agriculture and bioethanol production, including Indonesia and Thailand [37]
		Biodiesel: lower CO_2 concentration compared to bioethanol due to the nature of the transesterification process used, which does not produce CO_2 as a primary byproduct		Malaysia and Indonesia (the major biodiesel producers) [76]
Power Generation Industries	Wood chips, agricultural waste, energy crops	Biomass power plant: low CO_2 concentration (3-5%) [77]	Capturing and storing carbon from: • biomass power plant or biomass co-firing coal power plant emission • waste incineration to energy emissions, and • combining CO_2 emission with hydrogen produced in PtX	Indonesia, Malaysia, Thailand, and Viet Nam [78]
		Biomass co-firing coal power plant: moderate CO_2 concentration (16-17%) [79]		Coal-reliant areas in ASEAN (e.g., Indonesia, Philippines, Viet Nam, and Malaysia) [80]
		WtE: low CO_2 concentration (5-14%) [81]		Major urban centres with WtE facilities (e.g., Singapore, Malaysia) [82]
		PtX: varies depending on the process of CO_2 emission source		Areas focusing on hydrogen development (e.g., Singapore) [83]
Heavy Industries	Alternative fuels from biomass (e.g., wood waste)	Cement: high CO_2 concentration (exceed 30%) [84]	Capturing and storing carbon from heavy industries emissions	High cement demand areas (e.g., Viet Nam, Indonesia) [85]
		Steel: moderate CO_2 concentration (22%) [86]		Steel-producing countries (e.g., Indonesia, Malaysia) [87]
		Petrochem: lower CO_2 concentration (10-15%) [88]		Petrochemical hubs (e.g., Singapore, Thailand) [89]

Source: compiled from various sources

Efforts have been made to compare various industries that utilise biomass resources to evaluate the potential for BECCS applications. In general, higher CO_2 concentrations are preferable, as they simplify the capture process and reduce costs. Among these industries, bioethanol production from the biofuel sector exhibits the highest CO_2 concentrations. Hard-to-abate industries such as cement and steel also emit moderate to high concentrations of CO_2.

However, it is important to highlight the significant potential of biomass co-firing in coal power plants, which could serve as a readily available opportunity for BECCS implementation in Southeast Asia. This potential stems from the region's widespread adoption of biomass co-firing and the large volume of emissions generated. In Indonesia alone, the commercialised capacity for biomass co-firing is approximately 7.3 GW, further underscoring its viability as a BECCS application [90].

The journey towards effective and sustainable biomass utilisation in the ASEAN region is characterised by a diverse landscape of challenges and opportunities across different countries.

Brunei Darussalam stands out as having limited access to critical elements needed for biomass development, particularly in knowledge, skilled personnel, training facilities, and data reliability. The country shows potential in technology, and research and development efforts.

In contrast, **Cambodia**, **Lao PDR**, **Myanmar, the Philippines**, and **Viet Nam** exhibit a consistent readiness across all categories, indicating a strong foundation for biomass initiatives. These countries demonstrate a fundamental and comprehensive understanding of the technology involved, and have established frameworks for skilled personnel and training facilities.

Table 4. BECCS Development Status in AMS

Country	Knowledge Level[1]	Technology[2]	Research & Development[3]
Brunei Darussalam	N/A	N/A	🟡
Cambodia	🟡	🟡	🟡
Indonesia	🔵	🔵	🔵
Lao PDR	🟡	🟡	🟡
Malaysia	🔵	🔵	🔵
Myanmar	🟡	🟡	🟡
Philippines	🟡	🟡	🟡
Singapore	🔵	🔵	🔵
Thailand	🔵	🔵	🔵
Viet Nam	🟡	🟡	🟡

Note: N/A: not accessible; 🟡: lower; 🔵: higher[4]
Source: Author's compilation [42]

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[1] We assessed how widely information on biomass sources is shared among stakeholders in each country. Nations with active education and training programs on biomass were rated "higher," while those lacking such initiatives were rated "lower." Factors considered included the presence of biomass courses, workshops, and public awareness.

[2] We evaluated the availability and cost of biomass technologies. Countries where advanced technologies are more accessible or locally produced received a "higher" score, while those facing high costs, lack of expertise, or logistical issues were rated "lower."

[3] We analysed funding, research institutions, and innovation in biomass utilisation. Countries with active R&D programs and strong market support were rated "higher", while those with limited resources or slow market development were rated "lower".

[4] The results were summarised in a table using coloured icons to represent higher or lower scores across the three categories, allowing quick comparisons and highlighting areas for improvement.

Indonesia, Malaysia, **Singapore**, and **Thailand** display a higher level of preparedness, with robust systems in place for knowledge acquisition, skilled personnel, and data reliability. These countries not only excel in technology, but also invest significantly in research and development, positioning themselves as leaders in biomass utilisation within the region. Their higher ratings suggest a more advanced approach to overcoming the challenges associated with biomass, making them more capable of implementing effective strategies and innovations.

While the potential for biomass utilisation is evident across the ASEAN member states, the varying levels of preparedness show the need for tailored approaches to address specific challenges in each country. Collaborative efforts to enhance knowledge sharing, training, and technological development will be vital in advancing biomass utilisation in the region.

Technical and Economic Considerations

Unproven at Scale: While BECCS has been successfully demonstrated at pilot scales, its commercial viability remains largely unproven. The technology is still in its early stages, with only a few projects operating at a commercial level. As of 2019, the Illinois Industrial CCS facility is the only commercial-scale BECCS project worldwide, capturing approximately 1 million tonnes of CO_2 annually [33]. Despite being more amenable to quantitative modelling than many other negative emission technologies, BECCS remains a fledgling solution that has yet to be proven at scale [91].

Scaling up BECCS to the levels required to meet global climate targets presents considerable challenges. Studies indicate that areas suitable for large-scale deployment are limited, and integrating biomass production with carbon storage sites is a complex process [92].

In ASEAN, deployment faces additional hurdles, including a lack of technical expertise and insufficient infrastructure for carbon capture and storage. Many countries in the region have little experience with large-scale CCS projects, and geological storage capacity has yet to be comprehensively mapped.

High Costs: The implementation of BECCS technology faces significant economic challenges due to its high initial investment and operational costs. Without substantial financial incentives or a strong carbon pricing framework, these projects can be difficult to justify financially. This challenge is particularly pronounced in ASEAN, where many countries are still developing and may struggle to fund the large-scale infrastructure required for BECCS [93].

A report by the Boston Consulting Group highlights that BECCS projects require significant upfront capital, with costs ranging from $100 million to retrofit an existing facility—enabling it to capture several hundred kilotonnes of CO_2 annually—to over $1 billion for new facilities designed to capture millions of tonnes [94].

Additionally, a report by the EFI Foundation indicates that the cost of BECCS varies widely, from $20 to $400 per metric tonne of CO_2 captured, depending on the scale and specific application [42]. A study by the Nordic Council of Ministers further emphasises that high costs, coupled with insufficient financial incentives, remain major barriers to the widespread deployment of BECCS technology [95].

Efficiency Concerns: The performance of CCS technologies has also been underwhelming. Despite significant investments, only a handful of large-scale CCS plants exist, and many projects have stalled or been cancelled. Moreover, power plants equipped with CCS face efficiency losses, requiring 25% to 40% more energy to operate [96].

Additionally, concerns over the long-term safety of CO_2 storage, including potential seismic events and air pollution, persist. Current BECCS plants capture only 11% to 13% of their CO_2 emissions, and the technology itself consumes around 30% of a plant's energy output, raising doubts about the overall effectiveness of BECCS as a negative emission solution [97].

Environmental and Social Dimensions

Emissions Along Supply Chains: The entire lifecycle of BECCS, from biomass production to transportation and processing, can introduce additional emissions, potentially offsetting its carbon reduction benefits [98]. Lifecycle assessments (LCAs) of BECCS technologies highlight that emissions can arise at multiple stages, including biomass cultivation, harvesting, and transportation [99]. For example, emissions from transporting biomass can vary significantly, with road transport typically generating higher emissions compared to sea transport [100].

The International Energy Agency (IEA) further explains that emissions occur not only during biomass production and transport, but also throughout the energy conversion and carbon capture processes. These emissions can range from 10 grams to 30 grams of CO_2-equivalent per megajoule (gCO_2e/MJ) of biomass energy produced [23]. To mitigate these impacts, it is important of minimise transport distances and optimise processing techniques. Strategies such as using carbon-neutral power and organic fertilisers during biomass cultivation can significantly reduce lifecycle emissions associated with BECCS [100].

Resource Demands Beyond Land: Beyond land, BECCS deployment increases the demand for water and fertilisers, further straining essential resources. For example, growing switchgrass as a BECCS feedstock would require about 200 million hectares (nearly half the cropland in the U.S.) to remove 3.7 gigatonnes of CO_2 annually. This land competition can directly impact food production, diverting resources like water and nitrogen fertilizers away from crops, potentially leading to higher food prices and scarcity [68][93].

On a global scale, BECCS would consume 20% of the world's nitrogen fertiliser production—an activity that itself generates significant emissions—and require 4 trillion cubic meters of water per year, equivalent to all current global water withdrawals for irrigation. CCS operations also require substantial water; to sequester 12 gigatonnes of CO_2 annually would use 3% of the water currently consumed by human activities, though some can be recycled. Water demand estimates for BECCS vary considerably, ranging from 0.72 trillion to 24.4 trillion cubic meters annually, depending on biomass type and location [68][93].

In water-scarce regions, increased water usage for BECCS could lead to ecosystem degradation and loss of biodiversity in freshwater environments. Even if water consumption is moderated, the heavy use of fertilisers could still lead to pollution of water systems. Proper management of biomass production is essential to avoid environmental issues like deforestation, soil degradation, and biodiversity loss, which could offset the intended benefits of BECCS.

In ASEAN, home to some of the world's most biodiverse rainforests that act as major carbon sinks, unsustainable land-use changes could have severe global consequences. Additionally, the increased use of fertilisers and pesticides for energy crops risks polluting important river systems, threatening regional ecosystems [61] [101] [102].

The ASEAN region is located in tropical (moist and wet) climate zones, which studies have found more trade-offs than synergies between reducing greenhouse gas (GHG) emissions by using land for dedicated energy crops and achieving other Sustainable Development Goals (SDGs), particularly regarding water use and efficiency (SDG 6.4) [103].

For instance, oil palm production in Mexico has reduced watershed streamflow due to higher evapotranspiration rates, impacting water availability and forest sustainability (SDGs 15.1 and 15.2) [104] [105]. Similarly, sugarcane production in these climates and low-activity clay soils face water availability trade-offs. Similarly, eucalyptus production in tropical moist climates and high-activity clay soils leads to reduced streamflow, affecting water quantity (SDG 6.4) [106].

Analysing the use of biomass in Malaysia, for example, even in a general discussion of applying biomass as an energy resource, it poses significant challenges for biodiversity loss and water stress. In terms of BECCS, the issue of conflict between primary and secondary biomass sources, as previously mentioned, are closely related to land use and water requirements.

Therefore, it is imperative to follow the guideline in the National Policy on Biological Diversity 2022-2030, in ensuring there will be no environmental trade-offs by implementing BECCS in a country [107]. One significant concern is to reduce the pressures on biodiversity by maximising the use of secondary biomass sources, such as empty fruit bunches (EFBs), palm kernel shells, and palm fronds, rather than using primary biomass, which will need more land to be cleared and conflict with food production.

Infrastructure and Logistics

Infrastructure: In the ASEAN region, as shown in Figure 7, Indonesia dominates the landscape of biomass co-firing in coal-fired power plants (CFPPs), with approximately 80% of such facilities located within the country. This highlights Indonesia's significant role in adopting renewable energy sources [70]. In contrast, neighbouring countries have seen limited uptake. Singapore, Malaysia, and Thailand each have only one biomass co-fired plant, reflecting a slower transition to this sustainable energy practice.

The limited adoption of biomass co-firing in these ASEAN Member States (AMS) raises concerns about the compatibility of existing CFPP infrastructure with biomass as a supplementary fuel. Many plants were designed exclusively for coal combustion and lack the necessary modifications to efficiently handle biomass [108]. This technical constraint, along with economic and logistical challenges, has hindered co-firing efforts in countries like Singapore, Malaysia, and Thailand, where large-scale retrofitting of power plants would require significant investment [109].

A key challenge across these sites is retrofitting existing plants. Many CFPPs, such as Mae Moh in Thailand and Suralaya in Indonesia, were not designed for biomass combustion. Converting them requires costly and technically complex modifications. Biomass has a lower energy density than coal, meaning plants must either burn larger volumes or increase fuel input frequency to maintain energy output [110]. Upgrades to boilers, fuel storage, and feed mechanisms are necessary to accommodate these differences, increasing costs and causing potential disruptions during the transition.

A primary issue across these sites is the retrofitting of existing plants. Many CFPPs, such as Mae Moh in Thailand and Suralaya in Indonesia, were designed solely for coal combustion. The infrastructure modifications required to handle biomass, which has different combustion characteristics, can be both costly and technically complex.

For example, biomass has lower energy density than coal, which requires either larger volumes or more frequent fuel inputs to maintain the same energy output [108]. Existing boilers, storage systems, and feed mechanisms in these plants need upgrading to manage these different fuel requirements, which can drive up costs and disrupt power generation during the transition period.

Transportation and logistics further complicate biomass utilisation. In Indonesia, many CFPPs, such as Labuan and Pelabuhan Ratu in Java, rely on biomass feedstocks like palm kernel shells, rice husks, and forestry residues, which are sourced from different regions. Unlike coal, which benefits from well-established transport networks, biomass supply chains remain underdeveloped. Transporting bulky, low-energy-density biomass from rural agricultural areas to centralised power plants is costly, particularly for remote plants in Kalimantan, such as the Sanggau and Ketapang power plants, where infrastructure is limited.

Similar logistical challenges exist in Malaysia, where projects like Malakoff Corporation's co-firing trials at the Tanjung Bin Power Plant face significant hurdles. A centralised biomass collection and management system, along with efficient transport networks, is essential to ensure a stable supply. Without these, the large-scale deployment of biomass co-firing remains difficult.

Storage and handling also present challenges. Unlike coal, biomass is highly susceptible to moisture degradation and is harder to store in large quantities. Power plants such as Tanjung Bin, which are accustomed to compact coal stockpiles, must invest in specialised storage facilities to keep biomass dry and maintain its energy content. Furthermore, the seasonal nature of biomass production places additional pressure on storage systems to ensure year-round availability.

Processing biomass before combustion adds another layer of complexity. To burn efficiently alongside coal, biomass often needs to be processed into uniform sizes or densified into pellets. This requires investment in preprocessing facilities, either at the power plant site or nearby. For plants like Paiton and Pacitan in Indonesia, these additional infrastructure requirements could strain operational budgets and necessitate the development of new supply chains.

Grid integration is another factor that complicates the transition. Many CFPPs operate within large, centralised electricity grids optimised for coal. Biomass, with its more variable supply and lower efficiency, may require adjustments to grid management systems to ensure stability. In highly industrialised areas, such as Tembusu in Singapore, balancing grid reliability with the introduction of a less predictable fuel source poses a significant challenge.

Overall, the transition to biomass co-firing in ASEAN’s CFPPs is constrained by major infrastructure challenges. Retrofitting plants, improving transport and storage systems, building biomass preprocessing facilities, and integrating these changes into grid operations all require substantial investment. Without addressing these barriers, the economic and operational inefficiencies of biomass co-firing may outweigh its potential benefits.

Figure 7. CFPPs with Biomass Co-Firing in ASEAN

Source: Multiple sources

Transportation: The transport of CO_2 is a critical component of carbon management strategies and can be categorised into two main types: cross-border and domestic transport. Each method presents distinct logistical and economic considerations, particularly within the ASEAN energy landscape.

Cross-border CO_2 transport is primarily conducted via pipelines or shipping. Pipelines provide a continuous and efficient means of moving CO_2 over long distances, often linking industrial emission sources directly to storage sites. This method is particularly beneficial for large-scale operations, ensuring a steady flow of captured emissions without the need for frequent loading and unloading [111]]. In contrast, shipping offers a flexible alternative, enabling CO_2 transport to locations not connected by pipeline infrastructure. This is especially relevant in ASEAN, where geographical constraints, such as island formations and fragmented landmasses, make extensive pipeline networks impractical [112].

Domestically, CO_2 is also transported through pipelines or alternative means such as road and rail. Pipelines remain the most efficient option, allowing direct transfer between emission sources and storage facilities. However, in cases where pipeline infrastructure is lacking or where emissions sources are widely dispersed, road and rail transport may be necessary [113].

Given the relatively early stage of CO_2 transport development in ASEAN, lessons from other regions provide valuable insights. Europe, for example, has an established transport and storage infrastructure that offers competitive pricing. The MIT Economic Projection and Policy Analysis model estimates that the average cost of transporting CO_2 is approximately $10 per tonne across multiple countries, including the US, Russia, Canada, and Mexico. However, research by Smith, et al., suggests that costs vary significantly, particularly for pipeline transport and storage, ranging from $4 to $45 per tonne [114]. Europe's well-connected onshore pipeline network helps maintain lower costs by offering multiple transport options, such as truck and rail, a stark contrast to ASEAN, where infrastructure and geographical challenges significantly increase logistical complexity [92].

In the ASEAN, CO_2 transport costs fall into three distinct categories. The most expensive option, involving extensive pipeline networks, is estimated at $150 to $450 per tonne of CO_2. These high costs are driven by the durability requirements of long-range pipelines, which directly impact construction, operational, and monitoring expenses. Ensuring pipeline integrity over long distances remains a key challenge for ASEAN nations seeking to develop cost-effective carbon transport solutions [73].

The mid-range cost category, between $75 and $150 per tonne, includes a mix of offshore pipelines and ship transport. Nearly half of the total expense in this scenario comes from liquefaction, loading, and unloading processes at designated sites. While this approach presents a more feasible alternative to onshore pipelines, it still reflects the inherent logistical and financial constraints faced by the region [73].

The least expensive option, costing between $50 and $75 per tonne, relies on existing ship or pipeline connections to onshore storage sites. However, the lack of robust infrastructure remains a significant barrier. Many CFPPs in ASEAN, particularly those using biomass co-firing, are concentrated in Java, where the development of nearby storage sites is crucial. Without such storage facilities, ASEAN nations may have to rely on more expensive transport options, increasing operational costs and potentially undermining the viability of carbon capture initiatives [73].

A notable example is the Mae Moh Power Plant in Thailand, which integrates biomass co-firing. Transport costs for sequestering its emissions could be significantly reduced if the captured CO_2 were directed to storage sites such as the Bongkot oil and gas field in the Malay Basin of the Gulf of Thailand, or the Yadana gas field in Myanmar. However, this solution would require cross-border transport, necessitating bilateral agreements between ASEAN nations. These legal and regulatory complexities underscore the broader challenges in developing an efficient and cost-effective CO_2 transport network across the region.

Geological Storage: The pursuit of effective CCS solutions in the ASEAN region has garnered significant attention, particularly as nations strive to meet their climate commitments. While a number of potential CO_2 storage sites have been identified, particularly those highlighted in the largest emissions estimates (Figure 8), it is essential to acknowledge the broader landscape of proposed storage locations. Among these, several sites have been modelled, with a notable concentration offshore from Peninsular Malaysia and the regions of East Malaysia.

Offshore carbon storage sites present promising opportunities for BECCS deployment in ASEAN, yet their geographical distribution raises critical challenges—particularly in relation to Indonesia's Java Island. While Java accounts for approximately 80% of the region's CFPPs exploring biomass co-firing, it hosts only around 15% of the available CO_2 storage sites [115]. This imbalance underscores the need for strategic planning to integrate BECCS effectively within the region's largest emitting sub-sector.

Myanmar's Yadana gas field offers deep geological formations suitable for CO_2 storage, but the country's political instability and lack of regulatory frameworks pose significant barriers to large-scale BECCS implementation. Similarly, Thailand's offshore Bongkot oil and gas field presents a viable storage option, yet the high initial costs of retrofitting existing infrastructure and ensuring a steady bioenergy supply from the mainland remain key challenges.

In Indonesia, sites such as the Arun and Suban gas fields are located near major industrial and population centres, potentially streamlining bioenergy production. However, Indonesia's vast geography and decentralised energy infrastructure make CO_2 transportation both complex and costly. Additional promising sites, including the Tunu, Badak, and Tangguh fields in East Kalimantan and Papua, offer significant storage potential, given their proximity to high-biomass regions. Nonetheless, deforestation and land-use conflicts pose considerable hurdles to scaling up bioenergy projects in these areas.

Malaysia's Luconia and E11 gas fields, integrated into extensive offshore networks, provide ideal geological conditions for long-term CO_2 storage. However, despite Malaysia's progress in renewable energy, large-scale BECCS adoption requires substantial investment in new technologies and policy incentives that promote carbon reduction. Brunei's SW Ampa gas field, while geologically well-suited for CO_2 storage, faces limitations due to the small scale of its domestic bioenergy sector, necessitating regional collaboration or bioenergy feedstock imports.

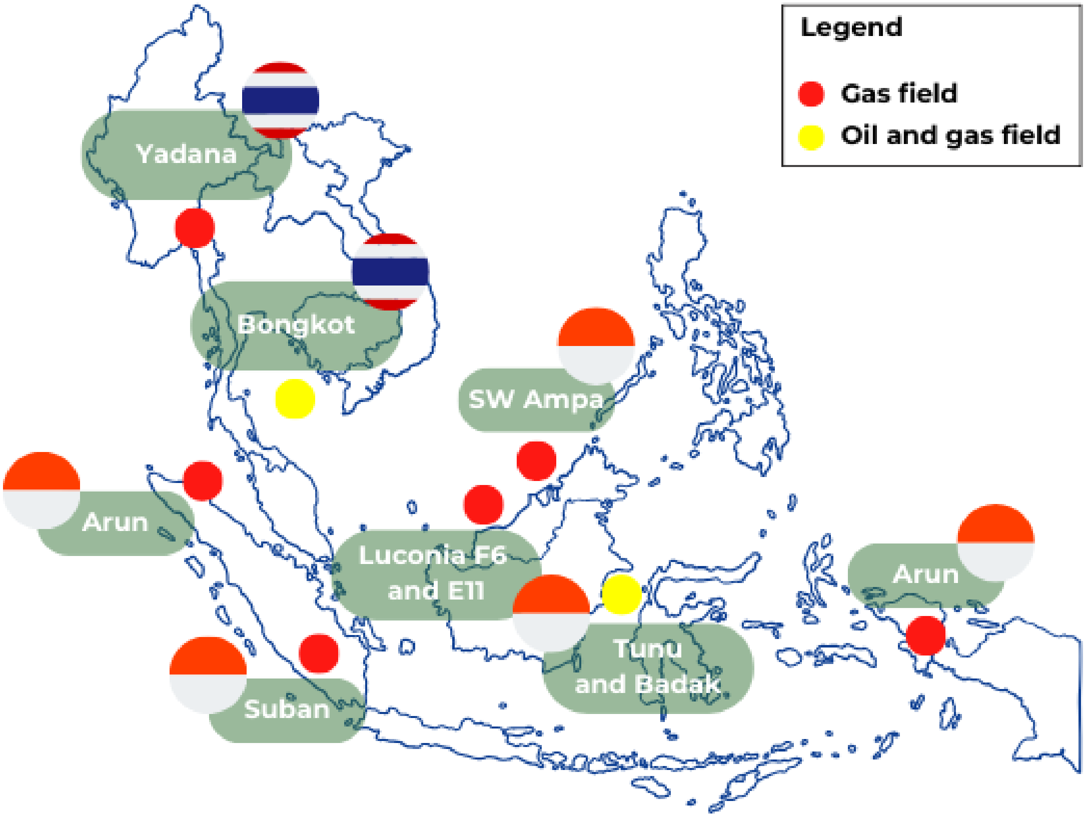
Although these storage sites hold significant potential, their development is hindered by high capital expenditures, the need for extensive CO_2 transport infrastructure, and ensuring the long-term stability of stored carbon. Furthermore, regulatory gaps and insufficient policy incentives across several ASEAN nations complicate the integration of BECCS into their energy transition strategies. Without strong regional cooperation and international financial support, large-scale deployment of BECCS in these locations may face considerable delays.

Addressing these challenges requires further exploration of storage sites located in closer proximity to major emission sources. Current proposals focus on storage hubs in Singapore and Malaysia, which offer certain logistical advantages, but also pose significant complications due to the high volume of emissions that would need to be transported. The infrastructure and operational costs associated with long-distance CO_2 transport could create substantial economic barriers to the widespread adoption of BECCS.

Moreover, the environmental and regulatory implications of transporting CO_2 over long distances must be carefully considered. Beyond escalating costs, such operations introduce safety concerns and require strict compliance with environmental regulations. As a result, the strategic identification and development of additional, more accessible storage sites will be crucial to facilitating the integration of BECCS into ASEAN's energy systems.

Maximising the potential of geological storage as a long-term carbon sequestration solution necessitates thorough assessment and risk management. Evaluating the capacity and stability of these sites is essential to ensure they can securely contain CO_2 over extended periods. Without comprehensive monitoring and scientific validation, the risks associated with leakage or geological instability could undermine the benefits of this technology. Bridging the gap between potential and practical application will require rigorous research, sustained investment, and coordinated efforts to establish the integrity and viability of geological storage solutions.

Figure 8. The 10 Largest Potential CO_2 Storage in ASEAN



Source: Li et al., 2022

Policy Recommendations

In addressing the challenges of implementing BECCS in ASEAN—such as land and biomass availability, technological and economic feasibility, environmental and social impacts, infrastructure, transportation, and storage capacity—this chapter provides targeted policy recommendations. As the demand for renewable energy sources grows, it is crucial to establish a cohesive framework that maximises the efficient use of biomass resources and CCS, while ensuring responsible management. Key steps include:

1. Prioritise Sustainable Biomass Supply

Ensuring a sustainable biomass supply is essential for the long-term viability and environmental sustainability of BECCS. One key strategy is to develop **integrated land use plans** that balance agricultural production, biodiversity conservation, and biomass cultivation. This involves **utilising marginal land** for perennial crops, which avoids competition with food, feed, and fibre production, supporting Sustainable Development Goal 2 (SDG 2) [103].

Further promoting sustainable biomass practices, **sustainability standards** for biomass production should be established, while investment in **capacity-building programmes,** and **research and development** can enhance knowledge and practices. A **coherent policy and regulatory framework** is needed to address land-use competition and ensure environmental sustainability. **Strengthening regional collaboration** will help harmonise policies, share best practices, and create **robust monitoring and reporting mechanisms** to ensure accountability and transparency.

2. Enhance Technological and Economic Feasibility

In overcoming the high costs and scalability challenges of BECCS, it is essential to support pilot projects that **demonstrate commercial viability**. This can be achieved by fostering **public-private partnerships** and providing **financial incentives**, such as tax breaks, low-interest loans, and clear carbon pricing mechanisms. These measures will help offset the high initial costs and attract investment in BECCS technology [92].

It is also important to **address safety concerns** related to long-term biomass co-firing and CO_2 storage. This can be achieved through comprehensive protocols and **monitoring systems** that ensure compliance and safety. Creating a **regional knowledge hub** for BECCS will facilitate **information sharing** and collaboration among ASEAN countries, collectively helping the region. tackle implementation challenges.

3. Address Environmental and Social Impacts

Conducting comprehensive **lifecycle assessments (LCAs)** for BECCS projects is crucial to identify and mitigate emissions along the supply chain, ensuring that carbon reduction benefits are not offset. Policies should promote **sustainable biomass production** practices that minimise resource demands for water and fertilisers, incorporating agroecological methods [115]. Clear **guidelines for water use** in BECCS operations must be established, prioritising water conservation and sustainable practices.

Engaging local communities in decision-making through advisory boards will ensure that **social impacts** are considered. Additionally, **educational programmes** can raise awareness among various stakeholders about the benefits and challenges of BECCS, ensuring that communities are informed and involved in the process.

4. Enhance Infrastructure, Transportation, and Storage Capacity

Investing in the necessary infrastructure for the successful deployment of BECCS is critical. This includes enhancing **transportation infrastructure**, particularly by establishing **closer storage sites** to emission sources, and fostering **bilateral and multilateral agreements** for streamlined CO_2 transport.

Governments should also assess and retrofit **existing coal-fired power plants** for biomass co-firing, supported by financial incentives. Additionally, **identifying new carbon storage sites** through geological surveys and exploring **decentralised storage solutions** will help address regional emission challenges.

Promoting **research and development** tailored to ASEAN's unique conditions, along with creating **knowledge-sharing platforms**, will drive innovation in BECCS technology. Finally, clear **regulatory frameworks** and **risk management protocols** are essential for ensuring compliance and maintaining safety standard.

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Contact

ASEAN Centre for Energy
Soemantri Brodjonegoro II Building, 6th Fl.
Directorate General of Electricity
Jl. HR. Rasuna Said Block X-2, Kav. 07-08
Jakarta, 12950, Indonesia
Tel. (62-21) 527 9332 | Fax. (62-21) 527 93350
E-mail: secretariat@aseanenergy.org
www.aseanenergy.org

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