International Renewable Energy Agency

SUSTAINABLE AVIATION FUELS IN SOUTHEAST ASIA

A regional perspective on bio-based solutions

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ABBREVIATIONS

1G	1st generation biofuel
ASEAN	Association of Southeast Asian Nations
ASEAN-SAM	ASEAN Single Aviation Market
ASTM	American Society for Testing and Material
ATAG	Air Transport Action Group
ATJ	alcohol-to-jet
CAAS	Civil Aviation Authority of Singapore
CAPEX	capital expenditure
CEF	CORSIA eligible fuel
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CPO	crude palm oil
EFB	empty fruit bunch
EJ	Exajoule
EU	European Union
FAOSTAT	United Nations Food and Agriculture Organization statistical data
FCI	fixed capital investment
FFB	fresh fruit bunch
FT	Fischer-Tropsch
GDP	gross domestic product
GHG	greenhouse gas
ha	hectare
HEFA	hydroprocessed esters and fatty acids
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
ICCT	International Council on Clean Transportation
IRENA	International Renewable Energy Agency
ISCC CORSIA	International Sustainability and Carbon Certification Carbon Offsetting and Reduction Scheme for International Aviation
IUCN	International Union for Conservation of Nature
Lao PDR	Lao People's Democratic Republic
LF	location factor
LTAG	Long Term Aspirational Goal
MADB	Malaysia Aviation Decarbonisation Blueprint
MBM	market-based measure
MFSP	minimum fuel selling price
Mha	million hectare
MJSP	minimum jet fuel selling price
MoU	memorandum of understanding
MSW	municipal solid waste
Mt	million tonne
NETR	National Energy Transition Roadmap (Malaysia)
NPV	net present value
OPEX	operating expenditure
PFAD	palm fatty acid distillate
PKS	palm kernel shell
POME	palm oil mill effluent
POME oil	oil derived from palm oil mill effluent
PPP	purchasing power parity
RED	Renewable Energy Directive
RSB	Roundtable on Sustainable Biomaterials
SAF	sustainable aviation fuel
SAP	State Action Plan
SDG	Sustainable Development Goal
SIA	Singapore Airlines
t	tonne
THB	Thai baht
TRL	technology readiness level
SPK	synthetic paraffinic kerosene
UCO	used cooking oil
USD	United States dollar
yr	year

KEY FINDINGS

The findings of this report emphasise the urgency of accelerating the sustainable scale-up of biofuel supply chains in Southeast Asia. In the near term, biofuels remain the most viable option for significantly reducing aviation emissions. However, securing feedstock, especially from energy crops, is not something that can be achieved overnight: it requires strategic planning, infrastructure and investment. Careful planning, informed by science with social dynamics considered, especially in the context of Southeast Asia, should begin as soon as possible to minimise the risk of unintended environmental impacts. Below are key findings and recommendations.

PRODUCTION POTENTIAL

- Relying solely on residues and waste for sustainable aviation fuel (SAF) in Southeast Asia is risky due to competition with other uses and cost challenges.
- Growing energy crops on under-utilised low-carbon land will be essential, but their cultivation requires careful management.
- Recognising that Southeast Asia's feedstock and land resources vary significantly makes cross-border trade and foreign investment crucial to meeting regional SAF targets.
- Strategically allocating feedstock among different end uses will be critical considering that limited options are available to decarbonise the aviation sector.
- Engaging local stakeholders and tailoring strategies are essential in SAF production, especially where rural development and resource governance are priorities.

ECONOMIC ASSESSMENT

- SAF is still costly, with production costs varying significantly across countries.
- Hydroprocessed esters and fatty acid (HEFA) technology offers the lowest capital expenditure (CAPEX), making it an attractive choice for early SAF development.
- Reliable, affordable feedstock for HEFA is key, as fluctuating vegetable oil prices impact costs. This requires careful planning of energy crop production that also generates co-benefits for rural development, job creation and environmental management.
- Fischer-Tropsch (FT) plants may achieve competitiveness at scale, but high upfront costs require strong financial support, incentives and policy backing.
- Governments must establish financial mechanisms, encourage public-private partnerships and promote regional co-operation to advance large-scale FT plant deployment.

REGIONAL PERSPECTIVES

- Progress in SAF development across Southeast Asia varies, with notable advancements in Singapore, followed by Malaysia, Indonesia, Thailand and the Philippines.
- On the demand side, most countries respond reactively to market signals and rely on mandates, not subsidies, to drive SAF adoption.
- On the supply side, SAF production is being actively promoted as part of industrial development, with fiscal and non-fiscal incentives given to attract investment.
- External players such as Australia, China and Japan are partnering with Southeast Asian countries for export-oriented SAF production, which, while intensifying feedstock competition, brings essential capital and technology.
- Sustainable feedstock sourcing is essential, especially as countries explore various energy crops to support SAF production.
- A regional SAF framework could help balance competition and enhance sustainability.
- A “book and claim” system might offer flexibility, enabling countries at different stages to meet SAF targets collaboratively.

RECOMMENDATIONS

I. A cross-sectorial framework for SAF development

- Establish reliable and consistent supplies of residues and waste as SAF feedstock.
- Establish clear guidelines for energy crop cultivation.
- Reassess feedstock allocation for different end uses.
- Streamline policy co-ordination for efficient SAF implementation.

II. A co-ordinated regional framework for SAF development

- Develop a regional framework to facilitate trade.
- Foster regional collaboration for SAF deployments.
- Tailor policy support to regional variations.

INTRODUCTION

In recent years, a growing awareness of climate change, industry responsibilities and the urgent need for sustainability has gained momentum in the aviation sector, which is responsible for approximately 2-3% of global anthropogenic emissions. A pivotal step towards emission reductions was reached during the 37th Assembly of the International Civil Aviation Organisation (ICAO) in 2010, held in Montreal, Canada. Actionable objectives were established to enhance the industry's efficiency and set carbon-neutral growth goals, making the aviation sector a leader in this effort. A framework was introduced for ICAO and its member states to identify and implement solutions to reduce greenhouse gas (GHG) emissions, covering four key areas:

- State Action Plans (SAPs)
- SAFs
- market-based measures (MBMs)
- global aspirational goals.

Commencing in 2012, each ICAO member state agreed to submit its SAP, outlining a basket of measures for the respective state to employ to reduce its emissions, including current actions, actions in progress and near-future activities. The basket of measures by each respective state is tailored to the state's level of development, its circumstances, and the assistance or support required. The submission of a SAP helps ICAO to assess the progress made in achieving the global aspirational goal for aviation decarbonisation.

Additionally, a global scheme for MBMs, known as CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation), was developed and adopted by ICAO in 2016. CORSIA covers operations, infrastructure, aircraft technology, SAF, and carbon credits and trading (ICAO, 2024a). The scheme is implemented in three phases: a voluntary pilot phase (2021-2023), a voluntary first phase (2024-2026) and a mandatory second phase (2027-2035) for member states (see Box 1). A net-zero target by 2050 and a carbon-neutral growth path, known as the Long Term Aspirational Goal (LTAG), was set within the CORSIA framework in 2019. Experts from around the world working under the ICAO's LTAG Task Group have simulated and derived the scenarios leading up to 2050 (ICAO, n.d.a).

Box 1 Current status of CORSIA

To ensure CORSIA's effectiveness, a three-phase approach was implemented that gradually ensures the adoption of CORSIA by member states. Currently, all CORSIA member states are in the voluntary phase, which consists of the Pilot Phase (2021-2023) and First Phase (2024-2026). In the voluntary First Phase, member states perform trials (pilots) and demonstrations of CORSIA requirements compliance (such as reporting, compliance with CORSIA frameworks and standards, and emissions offsetting). The voluntary phase, set to end in 2026, will demonstrate member states' readiness. Their readiness will then determine whether a re-assessment in criteria, framework and reporting may be required for the mandatory phase (or Second Phase), which runs from 2027 to 2035.

To ensure its adoption by member states, CORSIA has also released tools and standards, such as the CERT tool (CORSIA CO_2 Estimation and Reporting Tool), CORSIA Eligible Fuel (CEF) reference, CORSIA Eligible Emissions Unit reference and the CORSIA Central Registry (CCR). These tools help to ensure good governance in data and reporting to CORSIA, supporting the traceability of decarbonisation for the sector.

Furthermore, to support the practical implementation of SAF, CORSIA also has a "book & claim" mechanism. This mechanism ensures access to SAF's sustainability certificates even for countries who lack the access or capability to produce a SAF. This is further discussed in Chapter 3, Section 3.

Considering the challenges posed by aircraft fleet electrification, SAF derived from sustainable bio-based feedstock is seen as a major contributor to achieving GHG reduction and to achieving net zero by 2050 (IRENA, 2021). ICAO's LTAG Integrated Scenarios 2 and 3 project that SAF could contribute 40-60% of aviation emissions reduction by 2050. Meanwhile, the International Air Transport Association (IATA) estimates that SAF will need to account for 65% of the aviation sector's required emissions reduction by 2050 (IATA, 2023).

Deploying SAF requires developing individual "process bricks" and connecting them to mature the entire supply chain. These "bricks" include feedstock collection, cultivation, processing, refining, blending, certification, validation, traceability, distribution and cost management. This deployment represents a new phase in the aviation energy transition, unlike anything seen before. The SAF industry is still in its infancy, with a current global production capacity of less than 1% of global aviation fuel usage. By the end of 2024, IATA estimates that the production of SAF will only reach 1.5 million tonnes (Mt; 1.9 billion litres), or 0.53% of global aviation fuel needs (IATA, 2024).

The Air Transport Action Group (ATAG) states that 330 Mt of SAF will be needed around the world by 2050 (Blanshard *et al.*, 2021). However, the situation differs significantly by region. The significance of regional contexts, particularly in terms of feedstock production, cannot be overstated. The availability of feedstock is closely tied to geographical, biophysical and socio-economic factors, especially within the land-based sectors. A key component in the energy transition is to "align energy infrastructure development planning to socio-economic development agendas and priorities" (RES4A, IRENA and UNECA, 2022). For regions with extensive agriculture and forestry sectors, creating synergies with existing economic activities is a priority to achieve multiple Sustainable Development Goals (SDGs) and prevent climate change.

In 2021, the International Renewable Energy Agency (IRENA) published a report summarising the global progress and potential of bio-jet fuel production (IRENA, 2021). While it offered a comprehensive global overview, there is a need to consider regional contexts for a deeper understanding. In this regard, Southeast Asia stands out, gaining significant attention in the urgent push for SAF.

Southeast Asia is rich in biodiversity, and the region relies heavily on extensive agricultural and forestry activities. As it navigates the complexities of decarbonisation, leveraging bio-based resources for fuel purposes becomes a focal point in addressing the trilemma of achieving equitable economic growth, sustainable land management and a just energy transition (IRENA, 2023; IRENA and ACE, 2016). The ongoing energy transition in the aviation sector provides a compelling opportunity to transform conventional land-based economies from unsustainable land exploitation to the sustainable use of resources for food, fuel and materials.

Furthermore, Southeast Asia has significant air traffic and a high dependence on tourism. It is an important transit hub, commanding approximately USD 117 billion (United States dollars) of global tourism spending. This amounts to close to 7% of a USD 1.7 trillion industry (UNWTO, 2019), and in the pre-COVID world the region had the fastest year-over-year growth, at 7%. The impact of business and tourist travel in Southeast Asia contributes roughly 12% to the region's gross domestic product (GDP) (Saberwal, 2022), supporting millions of people directly and indirectly. Policy development in the European Union is expected to have a significant impact on Southeast Asia, given the high volume of flights between the two regions.

At the same time, the countries that make up Southeast Asia have a wide range of development statuses, with countries at different speeds and stages of development. This makes the region an important area to study with regard to the impact of the transition towards sustainable aviation development for decarbonisation.

This report provides an overview of, and perspectives on, SAF development in Southeast Asia. It first estimates the potential volume of SAF that can be produced from sustainable feedstock in the region, including exploring energy crop production on under-utilised low-carbon land. This is followed by an economic assessment of various ICAO-approved pathways through techno-economic analysis in selected countries with planned SAF projects. The next chapter analyses the policy framework and investment activities within the region, and explores strategies tailored to the respective countries' resources. Finally, future perspectives regarding SAF in the context of energy transition, the aviation sector and SAF development within the region are presented as recommendations. Notably, the results presented in this report were discussed and reviewed by country representatives and industrial experts via a series of workshops and interviews.

1. PRODUCTION POTENTIAL

1.1 SCOPE

Technically, SAF can be derived from a range of bio-based resources such as vegetable oils, animal fats, carbohydrates, sugars, and residues and wastes from agriculture, forestry and municipal solid waste (MSW). Southeast Asia, with its extensive agriculture and forestry sectors, holds substantial potential for bio-based feedstock. Additionally, advanced feedstocks like algae are being explored in the region due to its suitable biophysical and climatic conditions. Depending on feedstock characteristics, various conversion processes can be employed to produce aviation fuel compatible with existing aircraft (ASTM D7566).

As a means to decarbonise the aviation sector, SAF needs to possess a significantly lower carbon footprint if it is to serve as an alternative to conventional jet fuel. Achieving this largely depends on the type and source of feedstock (ICAO, 2024a). To this end, sustainability criteria governing the utilisation of feedstocks were introduced by ICAO into CORSIA. Initially, the discussion focused mainly on various residues and waste streams. Despite studies highlighting the potential and co-benefits of mobilising under-utilised low-carbon land (De Carvalho *et al.*, 2019; Jaung *et al.*, 2018; McCormick *et al.*, 2014), the use of energy crops was largely excluded from major discussions in the sector. However, in early 2024, a European Commission report emphasised that energy crops dedicated to biofuels grown on marginal or abandoned lands will play a significant role in decarbonising the aviation sector (European Commission: Directorate-General for Research and Innovation, 2024).

To provide a holistic view of feedstock availability, this study considers two broad groups of feedstocks, namely i) residues and wastes and ii) energy crops from under-utilised low-carbon land. In terms of geographical coverage, Singapore and Brunei Darussalam are excluded from the feedstock analysis due to their comparatively lower agricultural development and lack of significant land mass. However, both countries are considered to be major off-takers in the analysis due to their potential demand for SAF.

1.2 MATERIALS AND METHODS

Residues and wastes

Several categories of residues and wastes were considered (Table 1). The estimation of the potential volumes of agricultural residues was largely based on that established in the 2023 IRENA report *Agricultural residue-based bioenergy: Regional potential and scale-up strategies* (IRENA, 2023). Assuming the year 2022 as the baseline year, statistical data from the United Nations Food and Agriculture Organization (FAOSTAT) (FAO, 2023a) was used as the main source to obtain crop production volumes.

The dry weight of the crop residue is first calculated by multiplying the amount of crop produced by the residue-to-crop ratio and subtracting the moisture content of the crop residue. The technical volume of biomass feedstock is then calculated by subtracting the theoretical volume with the recovery rate and the utilisation rate of the feedstock in existing competing uses, but does not consider future competitions from, *e.g.* shipping or biochar applications. The residue-to-crop ratio of each agricultural biomass and the moisture contents of feedstocks are obtained from the 2023 IRENA report (IRENA, 2023) and crossed-checked with literature, assuming the same ratios are applicable to all studied countries. However, in this study, the recovery rates and utilisation rates assumed are further refined specific to each country. Their values were gathered from respective government publications and existing literature work, and revised based on inputs received during stakeholder consultations and external reviews. For recovery rates and utilisation rates that could not be found in either type of source material, the same values used in the 2023 IRENA report (IRENA, 2023) were used as assumptions.

Table 1 Feedstocks considered

CATEGORY	FEEDSTOCK
Agricultural residues	Palm empty fruit bunch (EFB), palm kernel shell (PKS), mesocarp fibre, sugarcane tops, bagasse, molasses, rice straw, rice husk, coconut husk, coconut shell, corn stover (stalk), corn cob, cassava peel, cassava stalk
Wood residues	Wood residues from processing mills
Waste oils	Used cooking oil (UCO), palm oil mill effluent (POME) oil, palm fatty acid distillate (PFAD)
Urban waste	Municipal solid waste (MSW)

The volume for wood residue was estimated based on data from FAOSTAT, defined as wood waste and scrap such as sawmill rejects, labs, edgings and trimmings, veneer log cores, veneer rejects, sawdust, and residues from carpentry and joinery production.

For UCO, the volume was estimated based on the GREENEA Analysis for 2019 and the population census in individual countries in 2022 (Badan Pusat Statistik, 2022; Department of Statistics Malaysia, 2024; General Statistics Office, 2022; National Institute of Statistics Ministry of Planning, 2021; National Statistical Office, 2023). The POME volume generated at the mills was estimated based on a residue-to-crop ratio of 0.67 (Kaniapan *et al.*, 2021; Supriatna *et al.*, 2022), and the oil fraction was assumed to be 0.65% based on the average of 0.6-0.7% from literature (Mohd Pauzi *et al.*, 2023; Yeoh *et al.*, 2022). The volume of PFAD was estimated based on a residue-to-crop ratio of 3.5-5% (Neste, n.d.), and an assumed oil fraction of 80% based on an average of 65-95% from literature (Rajo *et al.*, 2020).

The MSW recovery rate was based on the MSW collection rate reported by review and/or research articles. For countries with no data, 70.5% was assumed based on regional numbers (Kojima, 2019; United Nations, 2023).

Energy crops from under-utilised low-carbon land

The potential under-utilised land in each country was roughly estimated based on data taken from "Land Use" data from FAOSTAT (FAO, 2023b, 2023a). Agricultural land, forest land and artificial surfaces are excluded, and water bodies are not considered. The remaining land area was broadly adopted as under-utilised low-carbon land that can be further explored for growing energy crops. A range of studies has previously been conducted on individual countries in Southeast Asia to identify land suitability for agricultural expansion, considering more comprehensive sets of criteria such as soil fertility, water availability, slopes, climates, *etc*. (Jaung *et al.*, 2018). However, due to the high-level nature of this regional study, spatially explicit analysis was not performed to identify land suitability for different crops in terms of agroecological and climatic conditions. Additionally, socio-economic criteria like labour availability, land ownership and infrastructure were not considered. Thus, the results should be used with caution, serving only as rough estimates to explore the potential of energy crops in the region.

Generally, energy crops refer to both edible and inedible crops specifically cultivated for the purpose of energy generation that are typically fast-growing and resilient to climate change (Basu, 2018). In this study, three generic crops were used as benchmarks to estimate the potential of SAF generated from under-utilised low-carbon land: oil crops with an oil yield of 3 tonnes per hectare per year (t/ha/yr), sugar crops with a sugar yield of 9 t/ha/yr, and microalgae with an oil yield of 9 t/ha/yr. Microalgae can potentially grow on land unsuitable for traditional crops as well as water bodies. These benchmarks do not imply the endorsement of any types of crops and serve purely for the purpose of estimation.

Volume of SAF

To estimate the potential volume of SAF, the HEFA pathway was chosen for vegetable oils, animal fats and waste oil. Alcohol-to-jet (ATJ) was chosen for crops high in carbohydrates and sugars, and Fischer-Tropsch (FT) was chosen for lignocellulosic materials and MSW. These three pathways were chosen due to their being the most well-established conversion processes with high technology readiness levels (TRLs) of 7 to 9 (EASA, n.d.; Wang *et al.*, 2024). The volume of SAF was estimated by multiplying the amount of dry feedstock with the SAF yield as depicted in Table 2.

Table 2 Assumed SAF yield from the most common pathways approved by ICAO

PATHWAY	PROCESS YIELD (total fuel/feedstock [tonnes])	SAF FRACTION (%)	SAF YIELD (total SAF/feedstock [tonnes])
HEFA	0.75-0.83[a]	20-55	0.48[b]
FT	0.13-0.22[a]	40-70	0.10[c]
ATJ	0.56[a] (from ethanol or isobutanol)	60-70[c]	0.12[b] (biomass feedstock) 0.16-0.18[c] (sugar feedstock) 0.34-0.39[c] (ethanol or isobutanol)

Based on: a. (de Jong *et al.*, 2015); b. (Diederichs *et al.*, 2016); c. (Geleynse *et al.*, 2018).

Projected SAF demand 2050

The "current" consumption of Kerosene Jet A-1 was frozen at the 2019 pre-COVID-19 pandemic level (The Global Economy, n.d.) before any worldwide impact on air traffic. The demand for SAF in 2030 was based on the target of 10% blend (WEF, n.d.) and a year-on-year growth rate of 4.7% for Kerosene Jet A-1 consumption (Ure *et al.*, 2015). The demand for SAF in 2050 was based on the target of 70% blend anticipated by (IATA, 2023). As the fuel forecast for 2050 is far beyond the current estimation, the calculation was based on 2030 jet fuel demand. One factor contributing to the subdued outlook for jet fuel consumption is the improvements in aircraft fuel efficiency with advanced operations and technologies that allow airlines to operate with less fuel per mile (Geiger, 2024).

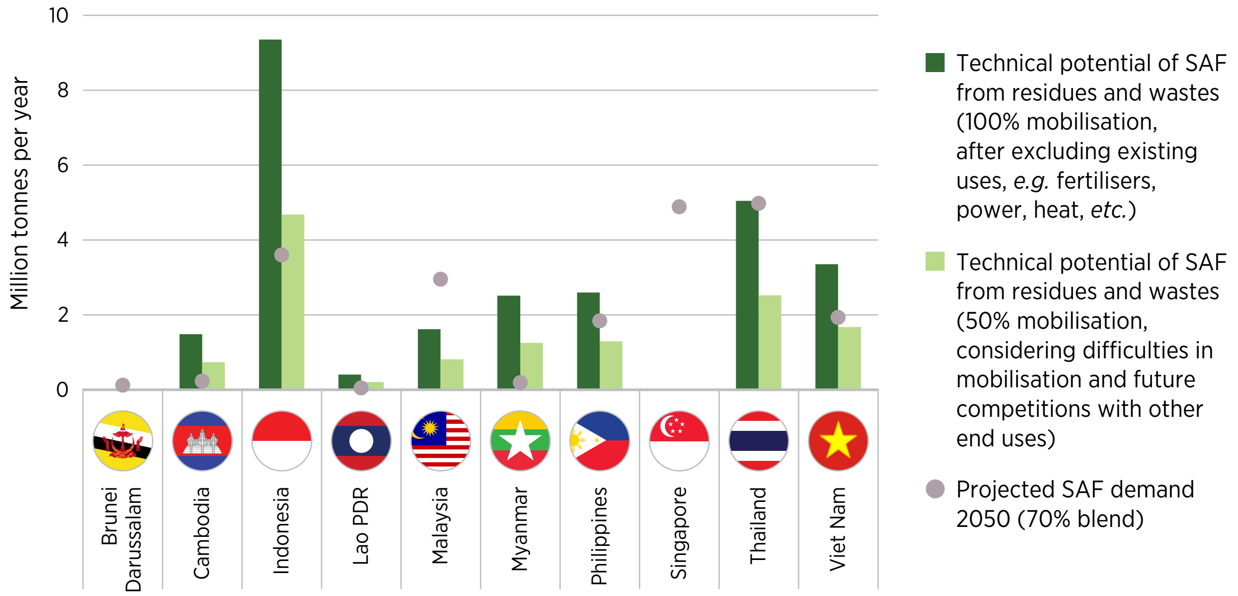
1.3 RESULTS

SAF from residues and wastes

SAF's total estimated technical potential from existing residues and wastes, compared with the potential with projected demand of 70% anticipated by 2050, is illustrated in Figure 1 (IATA, 2023). Aside from Singapore and Brunei Darussalam, Malaysia will not be able to meet the demand for SAF using domestic residues and wastes only. Thailand, the Philippines and Viet Nam can only reach the target with a very high mobilisation rate, *i.e.* the rate of available feedstock being efficiently collected, processed and converted.

Given future feedstock competition from other end uses, such as biomethanol for shipping and biochar for carbon sequestration, the gaps may widen. For example, in Singapore, the Maritime and Port Authority has indicated that the demand for methanol as a marine fuel may exceed 1 million tonnes per year (Mt/yr) before 2030 (Maritime and Port Authority of Singapore, 2024). To fully decarbonise the shipping sector by 2050 under the 1.5°C Scenario (IRENA and ACE, 2022), the demand for biomethanol in the region could increase 56-fold by 2050 (0.9 exajoules [EJ]). This would require approximately 40 Mt of lignocellulosic biomass to produce the biogenic carbon needed for decarbonising Southeast Asia's shipping sector, which could alternatively be used to produce around 4 Mt of SAF. Additionally, decentralised options such as biochar production or onsite power generation may be more strategically viable in areas where collecting residues and waste is challenging, particularly in regions with limited infrastructure and difficult terrain for transporting solid biomass. Therefore, it is essential to consider a scenario in which only a portion of available residues and waste can be mobilised for SAF production.

Figure 1 Potential volume of SAF from residues and wastes compared to projected demand in 2050



Notes: Technical potential = The technical volume of biomass feedstock is calculated by subtracting the theoretical volume with the recovery rate and the utilisation rate of the feedstock in existing competing uses, but does not consider future competition from, *e.g.* shipping or biochar applications. Lao PDR = Lao People's Democratic Republic.

Among the countries, Indonesia takes the lead as the country with the highest SAF potential, even when using residues and wastes only. As the world's largest palm oil producer, Indonesia generates a large volume of residues from its plantation sector. These residues amount to 7.5 Mt/yr out of the 9.3 Mt/yr of total SAF potential from agricultural residues. In contrast, although Malaysia is the world's second-largest palm oil producer after Indonesia, its SAF potential from residues and wastes remains low, at 1.6 Mt/yr. This is because a high percentage of the residues are already being used for various other purposes. Malaysia's technical SAF potential is further reduced because its second-largest stream of residues, coconut husks and shells, is destined for the activated carbon and charcoal industry (MPIC, 2023).

Thailand shows the highest demand based on the pre-pandemic data. This is because Thailand is among the most visited by foreign tourists and therefore experiences very high levels of international air travel (ASEAN, n.d.; Travel And Tour World, 2024). Relying solely on residues and waste, mainly rice straw and husks, the country can barely meet the target of 70% blend. The Philippines and Viet Nam exhibit similar patterns, with rice straw and husk contributing 57% and 78%, respectively, to their residue-based SAF potential. These three countries will be unable to produce sufficient SAF from residues and wastes if there is strong competition from other end uses, such as shipping fuel or biochar. Meanwhile, Lao People's Democratic Republic (Lao PDR), Myanmar and

Cambodia have the lowest jet fuel demand, aside from Brunei Darussalam. Notably, Myanmar and Cambodia demonstrate significant feedstock potential for SAF from residues and wastes.

Residues and wastes have been greatly emphasised as potential feedstocks for biofuels over the past decades and are considered sustainable alternatives to fossil fuels. In the European Union, these feedstocks receive extra incentives for blending into transportation fuels compared to crop-based feedstocks, driving the sector towards advanced technologies for converting lignocellulosic biomass into liquid biofuels. However, the production of liquid biofuels from residues and wastes has not yet reached the scale expected. In fact, the low-hanging fruit, mainly UCO and animal fats, has been greatly exploited for biodiesel production. To date, the European Union has attracted a large amount of UCO-based biodiesel from the world. Notably, Southeast Asia has been exporting UCO to China over the past decade, likely for conversion into waste-based biodiesel. This aligns with the significant increase in China's waste-based biodiesel exports to Europe in recent years (Mcgrath, 2020). Even so, only an average of 19% of UCO was collected in the Asian region (IRENA, 2021). One major reason is the lack of infrastructure and incentives for proper UCO disposal (Chanphavong, 2023).

Overall, waste oils are the smallest contributors of all the feedstock types explored. Indonesia and Malaysia are the exceptions to this trend, owing to their high POME oil and PFAD volumes. POME oil has recently garnered significant attention as feedstock for biofuels as the oil palm sector seeks incentives to manage the effluent from palm oil mills. Treating POME is crucial for protecting water resources and reducing substantial methane emissions. However, the exact amount of POME oil that can be collected for SAF remains uncertain. In Malaysia, the collection and trade of POME oil is already taking place, with these primarily being exported to China for biodiesel production, similar to the case of UCO. Generally, the supply-demand dynamics of POME oil are still under-studied (Yeoh *et al.*, 2022). The price of POME oil is reported to rise to roughly 90% of that of crude palm oil (CPO), a trend akin to UCO, driven by European Union (EU) incentives for waste-based biofuels. There is a risk that increasing demand for POME oil may prompt mills to adjust their processes to optimise the ratio of CPO and POME oil, balancing costs and profits while considering the investment needed to improve oil extraction efficiency. This could blur the distinction between POME oil as a waste stream and as a by-product.

The case of solid biomass is even more challenging. The low mobilisation rate of agricultural residues in Southeast Asia highlights the limitations of these resources, despite decades of promotion by governments and researchers as high-potential feedstocks. Firstly, it remains unattractive for agricultural stakeholders to invest in developing a biomass supply chain for liquid biofuels when residues can be used locally for decentralised purposes, such as local energy generation and mulching (Roszkowska and Szubska-Włodarczyk, 2022). In today's practice, most of the oil palm residues are either returned to soil as fertilisers and a carbon source or burned at the mills to generate heat and power. Meanwhile, rice straw and husk are currently partially utilised in farms as animal feed, soil compost and, on a smaller scale, made into higher-value products such as biodegradable packaging (Kadarsah *et al.*, 2023; MPIC, 2023). Farmers, however, tend to resort to open burning as a quick means of disposal, especially for rice straw. A survey in Viet Nam reveals that over 75% of farmers resort to open burning or incorporation of the residues into soil (Nguyen *et al.*, 2020).

Logistics costs remain the largest hurdle, considering the one-way collection, transport and storage of biomass in bulk volumes with low energy density (ASEAN, 2021; Rashidi *et al.*, 2022). Consequently, it is more practical to explore cost-effective local uses of biomass, including power generation, fertiliser production and processing into biochar to store carbon or various fibrous materials. These beg the question of how large-scale collection of the residues in Southeast Asia might be carried out. Furthermore, a substantial amount of biogenic carbon may also be needed for biofuel application in the shipping sector, which may greatly reduce the mobilisable feedstock. Due to high uncertainties in the actual amount that can be mobilised, relying solely on residues and wastes is very risky. Therefore, alternative approaches will need to be explored.

Box 2 Non-standard coconuts as feedstock

Indonesia and the Philippines, being world's major coconut producers, have been looking into the availability of non-standard coconuts for SAF production. Approved by ICAO as a CORSIA-eligible feedstock on 11 March 2024, non-standard coconuts refer to coconuts that have sprouted, are too small, are cracked or rotten, or are no longer fit for human consumption. They are categorised as "by-products", which are defined as "secondary products with inelastic supply and economic value" (ICAO, 2024b).

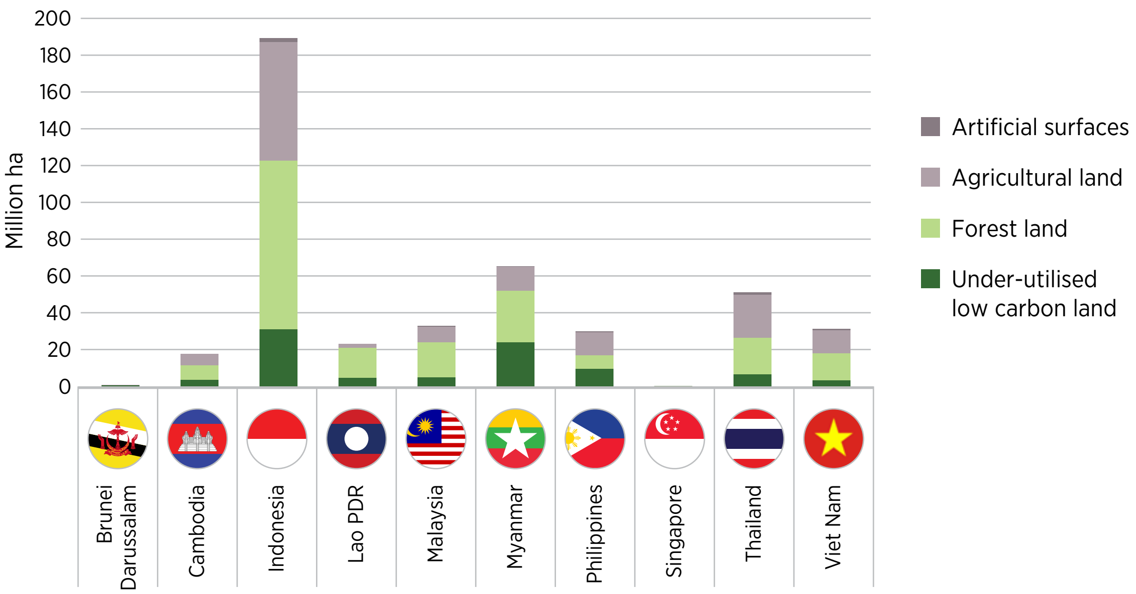
Indonesia claims non-standard coconuts account for 30% of its total annual coconut production (BRIN, 2024). Preliminary calculations for the region show that 0.27 Mt/yr of SAF may be produced from oil extracted from these non-standard coconuts through the HEFA pathway. In the meantime, if the shell and husk were also utilised through the FT pathway, the region could see another 0.35 Mt/yr of SAF, providing a total SAF potential of 0.62 Mt/yr.

Despite these calculations, up-to-date and comprehensive research on non-standard coconuts in ASEAN is lacking. As a result, there are high levels of uncertainty about data and a lack of concrete evidence to prove the significance of non-standard coconuts to the SAF feedstock industry.

SAF from energy crops from under-utilised low-carbon land

As relying solely on local existing residues and wastes is unlikely to meet current and future jet fuel demand in the region, exploring energy crops from under-utilised low-carbon land becomes a necessary alternative. This strategy is highly relevant for Southeast Asia, given its extensive history of land-based development activities. Ideally, biofuel production on under-utilised low-carbon land with insignificant ecological services can prevent carbon stock loss from forest conversion and potentially replenish lost carbon stock on degraded land.

Figure 2 Rough estimates of under-utilised low-carbon land area* in Southeast Asia



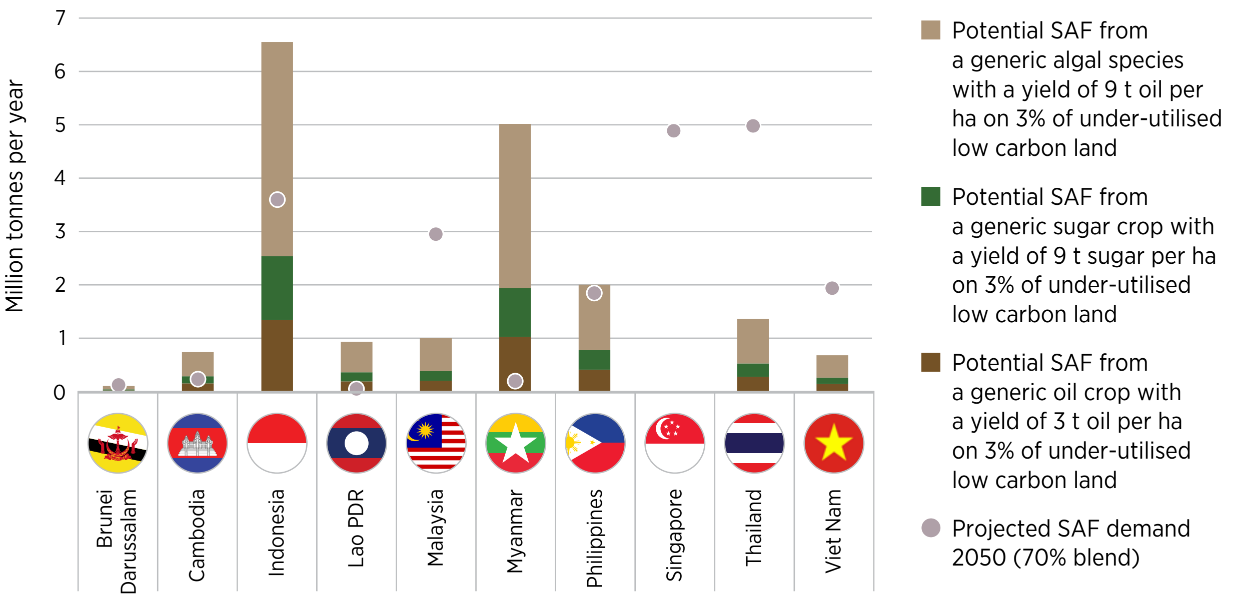
Note: *i.e.* land remaining after excluding forest land, agricultural land and artificial surfaces.
Based on: FAOSTAT (FAO, 2023b)

To date, terms like "abandoned", "degraded" and "marginal" land have been used to describe such lands, although definitions vary. For instance, Indonesia uses *lahan kritis* (critical land) and *lahan sub-optimal* (sub-optimal land) to indicate degraded lands, but these terms are not always clearly defined. Global estimates of degraded land vary widely, from 1 billion hectares (ha) to over 6 billion ha, due to different databases and methodologies. For the case of Southeast Asia, Figure 2 illustrates the rough estimates for under-utilised low-carbon land. Among the eight countries with under-utilised low-carbon land, Indonesia (with 31 million hectares [Mha]) was found to have the largest amount of under-utilised low-carbon land, followed by Myanmar (with 24 Mha) and the Philippines (9 Mha). Meanwhile, the remaining two countries fall into a range of 3 Mha to 6 Mha.

While these results indicate that land potential can be promising, one should treat these estimates with extra care. In the past, ambiguous land regulations, poor monitoring and bad governance have led to unrealistic expectations and unintended consequences. Fortunately, more accurate, high-resolution monitoring is becoming more accessible to developing countries as technology advances. Monitoring is thus crucial to understand how future expansion may occur on these lands. To make suitable plans for SAF production in different locations, it is necessary to consider agroecological, economic, social and institutional factors.

Crucially, this strategy has to be carefully aligned with the concepts of bio-economy and nature-based solutions (FAO, 2024; IRENA, 2022). It requires a holistic evaluation from a landscape perspective, emphasising comprehensive land and environmental management across entire landscapes rather than a narrow farm-based or plantation-based approach. This involves not only energy crop plantations but also the interconnections between various components, including people living across the landscape, food production, biodiversity, water systems, *etc*. A holistic approach facilitates the integration of biofuel production into larger systems, ensuring that agricultural expansion does not lead to unwanted consequences. Furthermore, as noted in a 2014 International Union for Conservation of Nature (IUCN) report, "the pressure to source biofuels from 'lower risk' land could create an incentive to invest in restoring degraded lands" (McCormick *et al.*, 2014). Importantly, the rigorous sustainability scrutiny unique to the biofuel sector can potentially accelerate efforts to improve land governance. Such incentives are crucial to drive changes in regions like Southeast Asia, where land governance has been challenging and financial resources for nature restoration are often limited.

Figure 3 Potential SAF from energy crops from under-utilised low-carbon land* compared with SAF demand at 70% blend in 2050



Note: * assuming a use of 9% of under-utilised low-carbon land.

To provide a quantitative basis for discussion, Figure 3 illustrates potential SAF production from generic energy crops grown on 9% of under-utilised low-carbon land in each country. This hypothetical scenario allocates 3% of this land to each type of energy crop: high-yield oil crops, sugar crops and microalgae. While the allocation is illustrative, this approach could yield a substantial volume of SAF, up to 18.4 Mt/yr, which is nearly sufficient to meet the region's total projected demand. Indonesia (6.5 Mt/yr) and Myanmar (5 Mt/yr) show significant potential, with their combined total exceeding the sum of the potential from the other countries. In terms of actual land area, Indonesia (2.8 Mha) has the largest land area allocated from the 9%, followed by Myanmar (2.1 Mha), the Philippines (0.9 Mha) and Thailand (0.6 Mha). The remaining countries fall below 0.5 Mha.

The question that follows immediately is about the choice of crops. Naturally, land suitability, farmers' preferences, and other various agroecological and socio-economic factors should be carefully considered. However, in the case of SAF, the discussion has been largely skewed towards demand-side factors. Based on the sustainability principles and criteria of biofuels set by the Roundtable on Sustainable Biomaterials (RSB) and ISCC CORSIA, most of these primary crops are not eligible for SAF due to RSB's Principle 6 on Local Food Security. Meanwhile, the American Society for Testing and Material (ASTM) revised the D7566 Annex 5 in 2018 to allow the use of ethanol from any renewable feedstock, including sugarcane, for the production of SAF (RSB, 2020). This change is especially crucial for Thailand, which is the fourth-largest global sugar producer (Sowcharoensuk, 2023) and the largest sugarcane producer in the region. It presents another market opportunity to diversify the sugarcane commodity for a high-value biofuel product. At present, Thailand's bioethanol production is mostly sourced from molasses and cassava and is not price-competitive compared to corn-based bioethanol (Prasertsri, 2023), so there is little evidence to prove that any sugars have been directed for commercial ethanol production.

In this context, the case of Thailand could be seen, to some extent, as a potential example of the food-versus-fuel controversy, considering a possible scenario in which production cannot catch up with consumption. Since the Ukraine crisis began in 2022, global sugar prices have risen to an all-time high (white sugar: USD 763/t; raw sugar: USD 616/t) since September 2011 (European Commission, 2024). However, production in Southeast Asia has been further impacted due to the El Niño-related drought. In late 2023, the Thai government approved a 10% increase (THB 2 [Thai baht] or USD 0.06) in domestic sugar prices to curb the increased production cost borne by farmers due to the droughts (Thepgumpanat and Setboonsarng, 2023). These have resulted in increased food prices for end consumers. Experts noted that this disruption is likely to affect the 2023/2024 growing season in the form of reduced sugarcane yields (Voora *et al.*, 2023).

Oil crops, particularly palm oil, are another subject of debate in the case of Southeast Asia. Although EFBs, POME and PFAD from oil palm mills are eligible for the ISCC CORSIA certification (ISCC, 2023), it should be noted that the EU's Renewable Energy Directive II and III (RED II & RED III) intend to phase out palm oil-based biofuels by 2030 and may only consider palm waste-based (POME and EFB) feedstocks for biofuel production (Directorate-General for Trade, 2024; European Union, 2018; Russell, 2020). This means that flights arriving in EU airports employing palm oil-derived SAF would not be eligible to fulfil the SAF blending mandate imposed within the region (2% from 2025 onwards).

Indonesia, however, has moved forward with using palm oil for SAF. The decision is based on the abundance of palm oil in Indonesia, which is the world's leading palm oil producer (Nugroho *et al.*, 2024). Currently, the SAF plant developed by Pertamina will be using palm kernel oil as feedstock. At least in the near future, palm oil-derived SAF may only be used for domestic flights in Indonesia and not international flights. In any case, the government will have to be careful with the sourcing of feedstock to ensure the use of SAF does not defeat the purpose of decarbonisation, *i.e.* generating more emissions in the production process.

These requirements on the demand side have driven the search for non-food energy crops from under-utilised low-carbon land. However, prioritising edibility before yield (considering land suitability) and production cost (including the conversion cost to SAF via *e.g.* HEFA or FT) may work against the optimal solutions from a supply-side perspective. Crops with the most suitable agroecological characteristics do not necessarily come from non-food crop feedstock. Large-scale use of land must be planned with extreme care to avoid not only unwanted environmental and social impacts, but also the economic consequences of failed projects, taking into consideration the fact that the financial barriers for Southeast Asia to fulfil its decarbonisation targets are already substantial.

Microalgae cultivation has gained attention as it does not require fertile land and potentially has a high yield in terms of oil. Oil is generally preferred over carbohydrates because the oil from algae can be directly converted into hydrocarbon-based fuels using currently available technologies, while carbohydrates from algae would need to undergo additional processing steps such as fermentation to be converted into alcohols (Baig *et al.*, 2018). Theoretically, microalgae bear higher productivity than plant crops and can be harvested within weeks instead of years of cultivation (*e.g.* oil palm) (Barbosa *et al.*, 2023). Additionally, Southeast Asian countries are well-positioned for microalgae production due to their biophysical and climatic conditions, which are tolerable for most species (Hossain *et al.*, 2020). Sarawak in Malaysia is the first in the region to announce algae-to-SAF facilities (Petronas, 2023). The first facility is a collaboration between Sarawak Energy, Sarawak Biodiversity Centre, Eneos Corporation and Chitose Group from Japan at Sejingkat, while the other facility is a collaboration between SEDC Energy and Petronas in Demak Laut. The cultivation will be scaled up to 405 ha (1 000 acres) that can produce about 500 000 t/yr of crude algae oil (Ling, 2023). However, to date, successful commercial microalgae oil production for SAF is yet to be seen.

1.4 DISCUSSION

International trade and investment

The discussion so far has not yet fully accounted for the role of Singapore and Brunei Darussalam as off-takers, which could significantly impact supply-demand dynamics. Additionally, Malaysia will be unable to meet its demand even if its supply is topped up with energy crops from 9% of its under-utilised land, as seen in Figure 3. Thailand is also expected to face feedstock deficits in the long run due to its higher jet fuel consumption. In contrast, countries like Cambodia, Lao PDR and Myanmar have lower jet fuel demands and substantial SAF potential. Alongside Indonesia, with its large surplus of under-utilised low-carbon land, these countries could potentially supply feedstock to meet the regional SAF demand.

The uneven distribution of resources implies that cross-border trade and mutually beneficial partnerships will be essential. The trade of UCO highlights the complexities of feedstock availability. Although it is crucial for SAF's early adoption, sourcing UCO internationally presents challenges, particularly after the demand surge driven by the European Union's double-counting mechanism for biodiesel blending. UCO qualifies as a CEF under ICAO's CORSIA and is also certified as an approved feedstock under Europe's RED II. UCO is a key feedstock for HEFA-derived SAF, which companies like Neste utilise. Due to the strong demand for SAF, particularly through the HEFA pathway, the need for UCO is high. Europe, which relies heavily on the HEFA route for SAF production, will increasingly depend on imported UCO, potentially from countries like China, to meet its SAF targets. A recent report from ING states that the Asia Pacific region's HEFA capacity (both current and planned) will require about 10 Mt of feedstock, and estimates by the International Council on Clean Transportation (ICCT) put UCO supply in the region at about 5 Mt (Geijer, 2024). To date, the supply of UCO remains questionable due to competition, varying restrictions and high uncertainties (Box 3).

Box 3 Current status of international UCO trade

China, India, Indonesia and Japan have imposed varying restrictions on UCO to strengthen their domestic positions. Indonesia tightened UCO export regulations, including palm olein and CPO, to stabilise local cooking oil prices and ensure sufficient supply (McGarrity *et al.*, 2022; Moffitt, 2022). India restricted UCO exports in April 2022, not only to secure feedstock for its biodiesel programme but also to prevent waste oils from re-entering the food market (Das, 2024; Srivastava, 2021). The Food Safety and Standards Authority of India estimated that of 3 Mt of UCO generated in 2021, 60% was repackaged for food use, particularly in roadside food stalls (Ministry of Health and Family Welfare India, n.d.).

In Japan, while no formal ban exists, Japanese refiners are increasingly capturing the domestic UCO market, which produced 380 000 t between April 2021 and March 2022, of which 120 000 t was exported to Europe (BioEnergyTimes, 2024; Quantum Commodity Intelligence, 2024). The Ministry of Economy, Trade, and Industry is promoting local SAF production, with Tokyo planning to invest USD 2.3 billion by 2024/25 through green transformation bonds to meet a 10% SAF consumption target by 2030 (Hasegawa, 2024).

China, the global leader in UCO collection and export, faces challenges in meeting its own SAF demand. The country will need at least 2.94 Mt to meet SAF and domestic transport fuel needs by 2030 (European Federation for Transport and Environment, 2024). In 2023, China collected 3.38 Mt of UCO, with a substantial amount exported. As China's SAF demand rises, UCO exports may decline, affecting dependent countries like the Netherlands, Singapore, Spain and the United Kingdom as well as the rest of Europe.

While dedicated energy crops can be grown to supplement jet fuel demand, their cultivation, particularly that of perennial plants, would still require a few years' time to reach maturity. Moreover, investment incentives may need multiple years to be rolled out to kickstart mass cultivation. Foreign direct investments are crucial to stimulate growth of the feedstock and SAF production activities in the countries that have the resources to do so and to open the door for feedstock and SAF trade. Notably, the region has also attracted investments from other countries in Asia and the Pacific, as seen with commitments from Australia, China and Japan to establish a SAF supply chain (Pandey, 2024). As of July 2024, Japan and Australia were facing jet fuel shortages because both countries experienced a greater number of air travellers (Kumagai and Vahn, 2024; Meacham, 2024). It is worth exploring whether international trade and investment could support increased SAF production in countries with higher potentials. Country-specific discussions and recommendations are made in Chapter 3.

Feedstock allocation between transportation sectors

The allocation of feedstock for different sectors will be essential to determine the decarbonisation strategies for the aviation sector. Domestically, the current biodiesel blending mandates are B35 in Indonesia, B20 in Malaysia, B7 in Thailand and B3 in Philippines (Moffitt, 2023a; MPIC, 2023; Rahmanulloh, 2023) (DOE Philippines, 2024)). This indicates that current oil feedstocks are already needed to meet the biodiesel mandates, increasing the scarcity of oil feedstocks for SAF production. Furthermore, the high market price of oil feedstocks makes SAF more susceptible to a high selling price (MIDF, 2024), which is a major deterrent for airlines to get onboard with the SAF-for-decarbonisation agenda (Biofuels International, 2024).

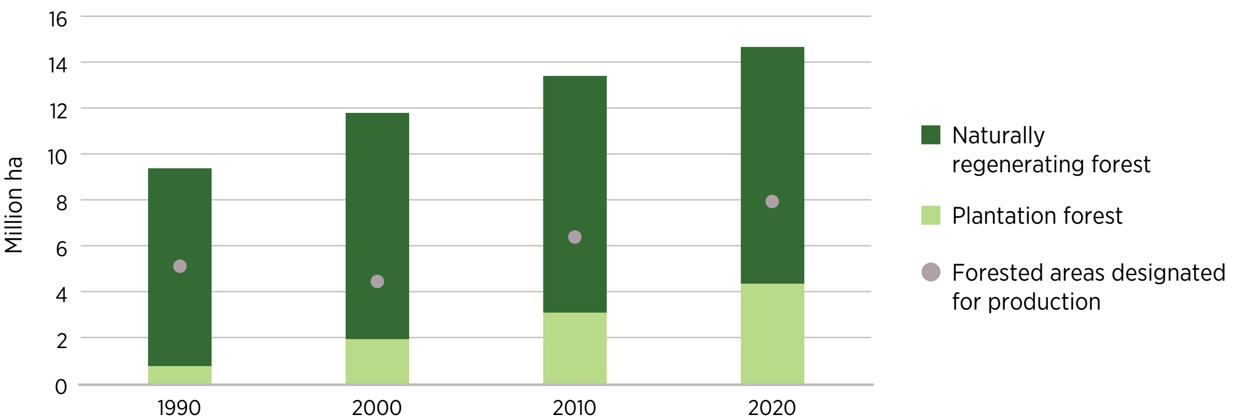
Malaysia and Thailand, which have incentivised and prioritised electrification of road vehicles (Prasertsri, 2023; Wahab, 2023), can divert their feedstock resources more quickly to decarbonise the maritime and aviation sector. A similar approach could also be taken by Indonesia, whose lower sales tax programme for flex-fuel vehicles (ethanol-powered vehicles) has not been well received (Rahmanulloh, 2023). For the remaining lower-middle income countries, there is little room for the consideration of feedstock allocation for in-house biofuel production due to the existing challenges related to infrastructure, investment and policy development (Balanay and Halog, 2024; IRENA, 2018).

Local conditions and labour availability for energy crops production

Given the scale of SAF demand, the involvement of local stakeholders, including farmers and communities, for both labour and land requirements must be carefully thought through. This is particularly important when rural development is positioned by policy makers as a main benefit of SAF production. Activating under-utilised low-carbon lands for SAF production creates new opportunities for smallholders, offering increased income sources, technical assistance and market access. Importantly, it also reduces the risks associated with unsustainable land use. These economic opportunities may incentivise improved resource governance, tapping into synergies with carbon and environmental management. In this regard, local socio-economic conditions, including familiarity and preference of farmers on different crops, will have to be given priority. These considerations raise the question of whether a national or regional policy framework could be established to support the development of an SAF ecosystem through the cultivation of crops that farmers and planters are or can be made familiar with, and ready to accept. Such an ecosystem would ease the transitional process to grow energy crops on a vast area of under-utilised low-carbon land dedicated to SAF feedstock production.

Viet Nam serves as an interesting case in the context of Southeast Asia. For decades, the forestry and wood processing industry has been a cornerstone of the country's economic growth and income generation, with a large number of smallholders involved. Over the decades, plantation forests have expanded remarkably, increasing by over 4 Mha from 1990 to 2020 (Figure 4). Furthermore, this happened alongside notable growth in naturally regenerating forests, exceeding 1 Mha. Viet Nam now ranks as the largest wood pellet producer in the region, with approximately 10% of the harvested woody biomass processed into wood pellets, which are subsequently exported for energy purposes (IRENA, 2022). This example demonstrates the possibility of contributing to both bioenergy production and carbon stock storage, emphasising strategic land management and active participation in international trade.

Figure 4 Changes in forested areas in Viet Nam, 1990-2020



Source: (IRENA, 2022; FAOSTAT, 2021).

However, it is important to consider that Viet Nam's success is partly due to its high population density and thus high labour availability per hectare of land. In contrast, countries like Indonesia have significant areas of under-utilised low-carbon land situated in sparsely populated regions like Kalimantan and Sumatra. Meanwhile, mid-income countries like Malaysia are facing a declining rural population and labour shortage in the agricultural sector. This presents challenges related to labour availability, and a large-scale migration of labourers from elsewhere may lead to negative social impacts as observed in the past (Goh *et al.*, 2017). Tailored strategies, including innovative business models, are necessary to ensure social sustainability. These aspects are further explored in Chapter 3.

1.5 KEY FINDINGS

- It will be risky to rely solely on residues and wastes to meet SAF demand in many Southeast Asian countries due to existing utilisation and future competition from other end uses, such as shipping fuels and biochar, as well as considerations of logistics and conversion costs.
- Energy crops will be necessary, but their cultivation must be managed with extreme care given the scale required. When selecting crops for biofuel, the focus should be on overall land-use sustainability and efficiency, rather than a narrow focus on only a food-versus-fuel debate. In any case, high-yield crops with minimal environmental impact and lower costs should be prioritised to use land and resources efficiently.
- Feedstock and land resources are not evenly distributed among the countries in Southeast Asia. Many countries could not be self-reliant for SAF supply, and the complexity of supply-demand dynamics across different end uses further complicates the situation. Resource-rich countries like Indonesia are poised to play a major role as key exporters in the biofuel market. Cross-border trade and foreign investment are essential not only to meet the targets in some countries but also to drive the development of SAF production in the region.
- Due to resource limitations, allocating feedstock between different end uses will be crucial, especially for the transportation sectors. Currently, vegetable oils and sugars are allocated for road transport, but in the future, hard-to-abate sectors like aviation and shipping should be given priority as there are no other options for decarbonisation.
- Involving local stakeholders, including farmers and communities, in land and labour planning is crucial for SAF production, particularly when rural development and sustainable resource governance are key objectives. Tailored strategies are essential for countries like Indonesia and Malaysia, where sparse populations or rural labour shortages present challenges, unlike Viet Nam, which benefits from high labour availability per hectare of land.

2. ECONOMIC ASSESSMENT

2.1 SCOPE

As of July 2023, 11 conversion processes for SAF production had been approved by organisations such as ASTM International, and 11 others were under strict evaluation (ICAO, 2024c). Eight out of eleven of the conversion processes are approved under ASTM D7566, which is the specification for aviation turbine fuels containing synthesised hydrocarbons. Meanwhile, the remaining three conversion processes follow the ASTM D1655 of the conventional standard aviation fuel specification, due to the nature of co-processing with conventional fossil jet (ICAO, n.d.a). The ICAO's approval process ensures that any SAF used by aviation not only meets environmental standards but also aligns with broader international regulations and market mechanisms. This helps in creating a standardised approach to SAF, facilitating global adoption and market penetration.

While numerous SAF production processes have been approved by ASTM International, this study focuses mainly on three pathways, namely HEFA-SPK (synthetic paraffinic kerosene), FT-SPK and ATJ-SPK, which are the most mature technologies to date. It is likely that the HEFA technology will be the most widely used in the coming years, as more planned plants are to be built, especially in Indonesia, Malaysia and Thailand (Praiwan, 2023; EcoCeres, 2023; European Commission: Directorate-General for Research and Innovation, 2024; Pertamina, 2023). Meanwhile, there is currently one FT plant announced for construction by WasteFuel in the Philippines (WasteFuel, 2021). Given the residues and waste that can be converted to SAF via the FT-SPK route, it remains an interesting option to be explored. The ATJ-SPK pathway is included due to the potential of sugar or starchy-based feedstock, especially sugarcane and cassava, in Thailand, Viet Nam and Cambodia. Table 3 shows the announced planned SAF production capacity in Southeast Asia. The ongoing investments in the respective countries will serve as a good indicator as to which countries have a higher potential capacity for SAF production.

The study will primarily focus on three countries: Indonesia, Malaysia and Thailand. Indonesia and Malaysia, as the leading palm oil producers, have just launched their specific road map or blueprint for SAF. Meanwhile, Thailand, with its extensive experience in bioethanol production, is developing a national plan for SAF.

The three countries also exhibit different supply and demand dynamics: Indonesia has a large surplus, Thailand struggles to meet potential demand and Malaysia faces a significant deficit. These countries are among the largest economies in Southeast Asia, contributing significantly to regional GDP. Malaysia's Kuala Lumpur International Airport, Thailand's Suvarnabhumi Airport and Indonesia's Soekarno-Hatta International Airport are major regional hubs that serve a large volume of international and domestic flights. Their economic prominence and strategic locations make them prime candidates for SAF adoption, which can significantly impact the region's aviation emissions. Additionally, the focus on using agricultural resources as sustainable feedstock for SAF not only appeals to the aviation sector but also bolsters the economy by creating new revenue streams for farmers.

Indonesia, as the world's largest producer of palm oil, has been an active SAF player in the region. The country generates significant amounts of agricultural residues and waste from its palm oil industry, which could be used as feedstock for SAF. The government released a national road map and action plan for the industrial development of SAF in September 2024 (Giam, 2024). Another pioneer in the region, Malaysia, launched the Malaysia Aviation Decarbonisation Blueprint in September 2024, emphasising the use of SAF to reduce sectoral emission up to 46.2%. Thailand is a key country to watch in the region due to its heavy air traffic as a major tourist and transit hub. The Ministry of Energy aims to finalise guidelines for SAF use by the end of 2024 (nationthailand, 2024).

Table 3 Non-exhaustive list of planned and operating SAF production plants in Southeast Asia

COMPANY	LOCATION	FEEDSTOCK TYPES	PRODUCTION START YEAR	ANNUAL PRODUCTION (T)	STATUS
Pertamina	Cilacap, Java, Indonesia	UCO, palm kernel oil	2026	418	Planned
NEXTCHEM	Sei Mangkei, Indonesia	UCO, POME	N/A	60 000	Planned
EcoCeres	Tanjung Langsat, Johor Bahru, Malaysia	UCO, POME	2025	220 000	Planned
Petronas & Idemitsu	Pengerang, Johor, Malaysia	Non-edible oil feedstock trees	2026	650 000	Planned
Petronas & SEDC Energy	Sarawak, Malaysia	Microalgae	N/A	N/A	Planned
Shanxi	Pengerang, Johor, Malaysia	UCO	N/A	N/A	Planned
Vandelay Venture	Kota Kinabalu, Sabah, Malaysia	UCO	2025	250 000	Planned
LOKEN	Malaysia	UCO, Biomass Oils	2025	N/A	Planned
FatHopes Energy & Lootah Biofuels	Malaysia	Waste oil	N/A	200 000	Planned
WasteFuel	Manila, Philippines	MSW	2025	91 000	Planned
Neste	Tuas, Singapore	UCO, animal fats	Q3 2023	1 000 000	Operating
Bangchak	Phra Khanong, Thailand	UCO	Q1 2025	292 000	Planned
PTT Public Company	Thailand	UCO	N/A	N/A	Planned
SAF One	Viet Nam	N/A	N/A	N/A	Planned
Nihon Toyo	Viet Nam	N/A	N/A	N/A	Planned

2.2 MATERIAL AND METHODS

The data used in this chapter are based on various literature studies from technology development (IRENA, 2017, 2021), techno-economical studies and real start-up plant data (de Jong *et al.*, 2015); (Klein-Marcuschamer *et al.*, 2011); (Pearlson *et al.*, 2013); (Swanson *et al.*, 2010); (Tanzil *et al.*, 2021); (Towler and Sinnott, 2008). The following sections describe the general material and methods used for this chapter.

CAPEX and the "nth plant" concept

Each SAF plant is assumed to be designed based on the feedstock availability and technology readiness of its particular country and mainly operated at a stream factor of 0.9 (for HEFA and FT) and 0.7 (for ATJ) due to harvest season considerations (Jones *et al.*, 2013). The stream factor is defined as the ratio of the number of days a plant operates per year to 365 days. For ATJ, a stream factor of 0.7 is generally considered low for a chemical plant, suggesting frequent shutdowns due to the feedstock supply being in batch mode (harvest season).

Capital cost data considered in this study include actual costs from commercial operations, estimates for early-stage plants (also known as pioneer plants), and projections based on the "n^{th} plant" concept for emerging technologies. The n^{th} plant concept typically refers to the fifth or later plant, with the specific number determined by expected learning rates. The methodology for estimating n^{th} plant costs usually involves applying the learning curve principle or the engineering cost and design estimation. The difference in costs between pioneering and n^{th} plants depends on the learning rate, with higher learning rates resulting in larger disparities. The learning rate in this context refers to the rate at which cost reductions occur as more plants are built and experience is gained. At lower learning rates, more plants may need to be built before reaching the n^{th} plant status of estimation. In summary, an n^{th} plant refers to a theoretical or hypothetical mature commercial facility in an industry, assuming that the technology has already gone through several iterations, achieving economies of scale, optimisations and reduced costs from learning and experience.

In this study, pioneering plant costs based on commercial plant data, typically higher than n^{th} plant estimates, are used for cost projections up to 2022. N^{th} plant estimates were used for cost projections depending on the technology's adoption rate. The rate of cost reduction will be influenced by the pace of new facility construction and capabilities to adapt from cost saving measures. Overall, these considerations highlight the importance of understanding the stages of development and associated cost data when evaluating different technologies. Based on the n^{th} plant concept, rapid cost estimates were conducted using literature and available commercial data (Towler *et al.*, 2008).

To consider building a similar plant in 2022, the capital investment was normalised to the year 2022 with the Chemical Engineering Plant Cost Index (Chemical Engineering, n.d.). Furthermore, factors such as the purchasing power parity exchange rate were included by estimating it using the consumer price index of the comparing countries. Notably, most plant and equipment cost data are given on a U.S. Gulf Coast or Northwest Europe basis. While the cost of constructing a similar plant in another location can be estimated by considering a location factor, this factor was not considered in this study due to lack of reliable data and high uncertainties.

Pioneer plant analysis

A pioneer plant analysis may be suitable to assess the potential of a technology in a near-term scenario. The method developed by the RAND Corporation is widely used in techno-economic assessments of novel biofuel technologies (Mukherjee *et al.*, 2023). This method involves conducting a multi-factor linear regression analysis on 44 production plants to pinpoint the key factors influencing capital investment escalation and reduced plant performance in the initial production year. Drawing from empirical data, RAND developed an equation to model the cost escalation of a pioneer plant, which is influenced by specific process details.

Operating expenditure (OPEX)

For OPEX estimation, the variable operating costs are first deduced. These variable operating costs encompass factors such as feedstock costs, waste disposal expenses and periodic costs. These costs are determined through a thorough examination of mass and energy balances, utilising the most up-to-date cost data available. In particular, feedstock costs and by-product revenues typically constitute the primary variable operating costs for these processes. To ensure accuracy and relevance, the costs sourced from the literature are adjusted to reflect the level in 2022 in USD using the Inorganic Chemical Index, a commonly used index in similar studies. This adjustment ensures that the variable operating costs align with current economic conditions and provide a realistic assessment of the financial implications associated with the processes under consideration. Table 4 provides estimates of feedstock prices to be used as baseline.

Table 4 Baseline feedstock prices

COUNTRY	FEEDSTOCK	PRICE (USD/TONNE)	REFERENCE
Thailand	Sugarcane	40	(Apisitniran, 2023)
Indonesia	Rice husk	30	(Dangprok *et al.*, 2023)
Malaysia	EFB	15	(Maitah *et al.*, 2016)
Thailand	Rice husk	30	(Dangprok *et al.*, 2023)
Indonesia	UCO	820	(Moffitt, 2023a)
Malaysia	UCO	900	(Moffitt, 2023a)
Thailand	UCO	900	(Moffitt, 2023a)
Malaysia	Algal oil	5 390	(Faried *et al.*, 2017)

Fixed operating costs are expenses that remain constant regardless of the plant's production rate, encompassing items such as labour and overhead expenses. The determination of fixed operating costs for the processes draws on methodologies outlined by (Humbird *et al.*, 2011) and (Jones *et al.*, 2013) to calculate labour and supervision costs using salaries sourced from literature, with an additional 90% labour burden included. Additionally, maintenance, property insurance and tax costs are derived based on the fixed capital investment (FCI). As no extensive investigation into fixed operating costs was previously conducted, a consistent number of 84 employees per plant was assumed for all processes except the HEFA process, which was assumed to have 52 employees due to its notably simpler process compared to FT and ATJ.

Minimum jet fuel selling price (MJSP)

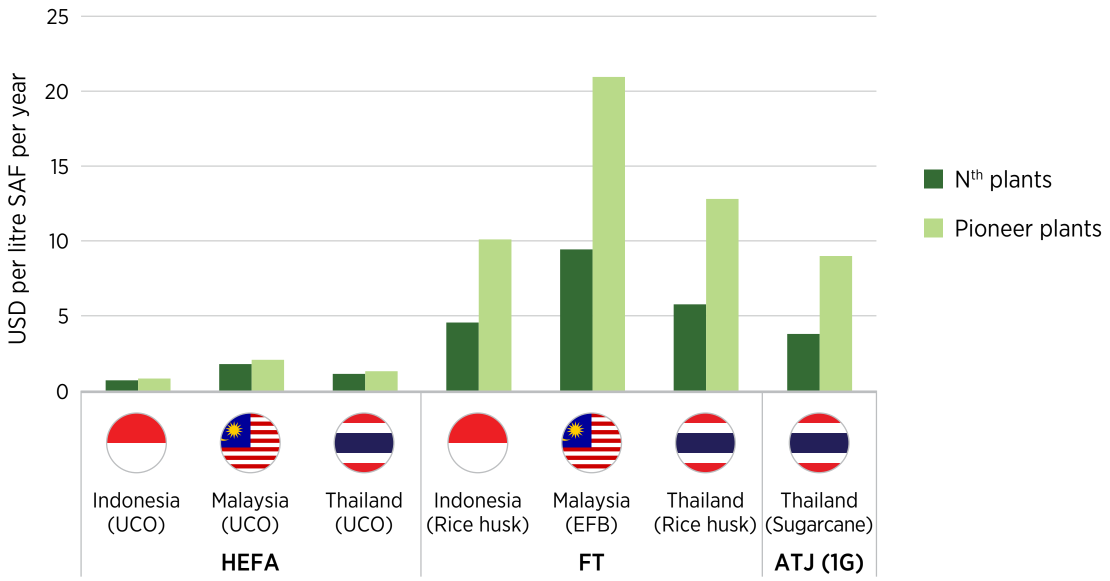
Following the determination of CAPEX and OPEX, a cash flow analysis was conducted following the methodology outlined by (Humbird *et al.*, 2011). Due to the uncertainty surrounding future jet fuel costs, the MJSP method is employed alongside the cash flow analysis to compare projects. MJSP is determined by adjusting the minimum fuel selling price (MFSP) on a jet fuel-equivalent basis to account for the difference in energy content between the biofuel and jet fuel to achieve a net present value (NPV) of zero at a specified discount rate, equivalent to the minimum acceptable internal rate of return. This metric allows for comparison between processes and assesses their economic feasibility by comparing MJSP to market jet fuel prices. Given that the MJSP for the processes exceeds market jet fuel prices significantly, the calculation of investment appraisal metrics such as NPV or discounted cash flow rate of return was deemed unnecessary. To facilitate comparisons between various processes, consistent assumptions for the economic parameters were employed based on literature (Jones *et al.*, 2013). To address the uncertainties from these assumptions, a sensitivity analysis was carried out to assess the impact of varying economic parameters on the MJSP.

2.3 RESULTS

CAPEX

Figure 5 shows the projected CAPEX for various pathways in Indonesia, Malaysia and Thailand on reaching n^{th} plant status in terms of USD per litre of SAF. The CAPEX for an FT plant in Malaysia is the highest among the three countries, nearing USD 9.5 per litre of SAF produced. Despite all three countries assuming a nameplate capacity of 2 000 t of feedstock per day, Indonesia benefits from lower construction costs. In contrast, HEFA plants have the lowest CAPEX values, with the one in Indonesia the lowest among all at USD 0.7 per litre of SAF. The differences between countries for the same pathway are primarily due to variations in PPP across the countries. The results suggest that although FT plants may become competitive once n^{th} plant status is achieved, the initial investment is very high.

Figure 5 CAPEX projection (n^{th} plants and pioneer plants) for SAF plants in Indonesia, Malaysia and Thailand



Notes: ATJ = alcohol-to-jet; EFB = empty fruit bunch; FT = Fischer-Tropsch; HEFA = hydroprocessed esters and fatty acids; MJSP = minimum jet fuel selling price; UCO = used cooking oil; USD = United States dollar.

Role of pioneer plants in cost reduction and technology advancement

Figure 5 also highlights the CAPEX for pioneer plants for the different technologies in all three countries, where the capacity of the HEFA plant is 250 000 Mt of SAF per year and both FT and ATJ plants have a capacity of 2 000 dry tonnes of feedstock per day. The FT pathway consistently incurs the highest CAPEX value for the "first of a kind" plant across the three countries, with Malaysia showing the most significant expenditure. In contrast, HEFA technology exhibits the lowest CAPEX for all three countries. It is also important to note that HEFA technology benefits from existing infrastructure and established processes from the renewable diesel industry. The CAPEX of a pioneer plant serves as a benchmark for future plants. As time progresses and more plants are built and operated, the industry is expected to gain experience and improve its understanding of the technologies. The learning process should lead to better design, optimised processes and more efficient use of resources. Technological improvements often lead to more cost-effective and efficient equipment and processes. As technology evolves, newer plants benefit from these advancements, which can reduce the CAPEX. As production volume increases, the cost per unit of equipment or infrastructure decreases, leading to lower CAPEX values for subsequent plants (Elia *et al.*, 2020).

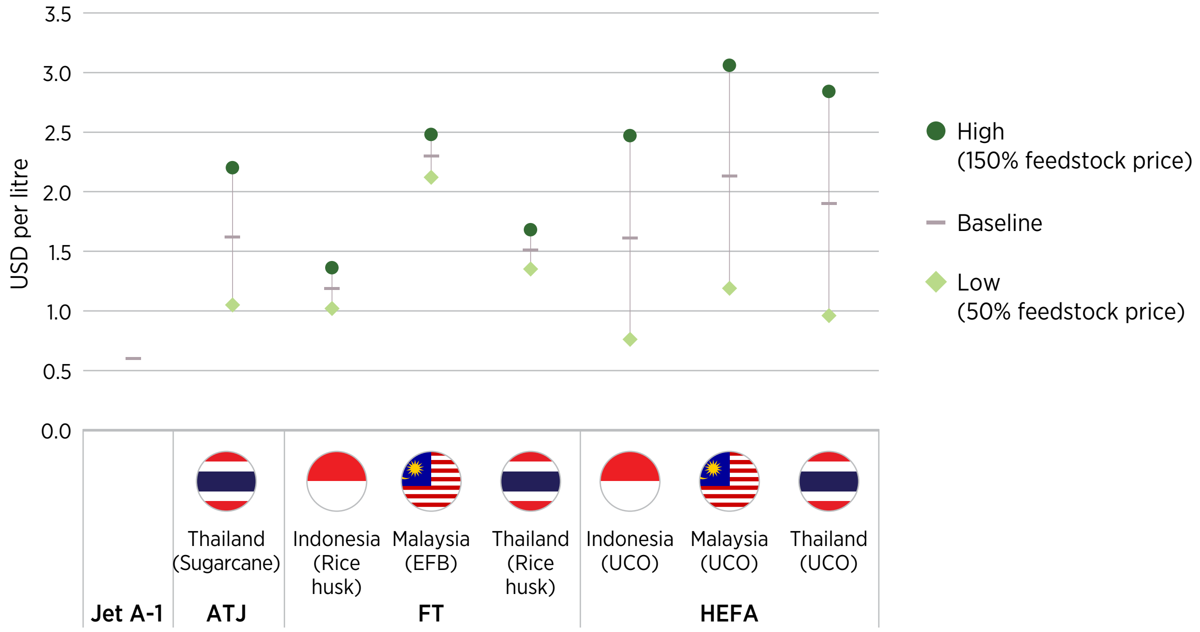
MJSP

Figure 6 presents the MJSPs for n^{th} plants across Indonesia, Malaysia and Thailand using various feedstocks via three pathways. Given that HEFA is already commercially available and can be produced in larger capacities within the region, the MJSP for HEFA ranges between USD 1.6-2.1/litre in the baseline scenario, approximately two to three times the fossil Jet-A1 price of USD 0.6/litre. The higher prices in Malaysia are largely due to differences in feedstock, labour and land costs. In comparison, the ATJ pathway using sugarcane as a first-generation feedstock in Thailand can achieve similar prices to HEFA at around USD 1.6/litre. Interestingly, despite high CAPEX, the FT pathway using rice husk as feedstock in Indonesia shows a much lower MJSP of USD 1.2/litre provided the n^{th} plant status is achieved.

Feedstock prices significantly impact the MJSP for oil-based SAF via the HEFA process, where a 1% increase in feedstock price results in a 1% rise in MJSP. In contrast, the MJSPs of SAF from lignocellulosic biomass are less sensitive to feedstock costs and more reliant on CAPEX. FT, in particular, remains uncompetitive until n^{th} plant status is achieved, requiring substantial investment – a major barrier in Southeast Asia, where financial resources for decarbonisation are limited.

Microalgae-derived SAF (not shown in the figure) is still prohibitively expensive, with MJSPs via HEFA estimated at USD 11.50/litre in Malaysia – nearly 20 times the current Jet-A1 price of USD 0.6/litre. However, open pond cultivation could significantly reduce these costs, making microalgae a promising option for the future, though it requires further study (Narala *et al.*, 2016).

Figure 6 Range of MJSPs of SAF derived from various feedstocks through different pathways in n^{th} plants in Indonesia, Malaysia and Thailand



Notes: ATJ = alcohol-to-jet; EFB = empty fruit bunch; FT = Fischer-Tropsch; HEFA = hydroprocessed esters and fatty acids; MJSP = minimum jet fuel selling price; UCO = used cooking oil; USD = United States dollar.

2.4 DISCUSSION

The results present key insights into the cost dynamics and potential of SAF production in Southeast Asia, highlighting both technological and economic challenges. The CAPEX for different SAF production pathways shows significant variation across Indonesia, Malaysia and Thailand. Malaysia's FT pathway exhibits the highest CAPEX, nearly USD 9.5 per litre of SAF. In contrast, Indonesia demonstrates much lower CAPEX for FT and HEFA pathways, with the latter as low as USD 0.7 per litre of SAF. HEFA, benefiting from established renewable diesel technologies, consistently shows the lowest CAPEX across all three countries, making it a more feasible option for early stage SAF development. The study indicates that while FT plants might become competitive at the n^{th} plant stage, initial investment costs remain prohibitively high, posing challenges for immediate deployment.

The implications of these results for Southeast Asia are complex and wide-ranging. First, SAF is not yet cost-competitive, with MJSPs still two to three times higher than fossil-based Jet A-1 kerosene. This presents a significant barrier for developing countries in the region, where maintaining affordable air travel is crucial, particularly for populations in island nations and remote areas. The high cost of SAF could strain efforts to make air transportation accessible, posing challenges for both economic development and social mobility in these regions. Policies and subsidies will be essential for large-scale SAF adoption. Foreign investment and technology transfer will be needed to alleviate some of these financial pressures, reducing the upfront costs of SAF production while accessing cutting-edge innovations.

The lower CAPEX for Indonesia, particularly for HEFA and FT pathways, positions the country as a potential key player in SAF production in the region. However, high initial investments for FT technology mean that further financial support and incentives will be necessary to realise these projects. Malaysia's high CAPEX across pathways highlights the need for targeted policy interventions to offset costs and stimulate SAF development. Thailand's lower-cost 1st generation biofuel (1G)-ATJ pathway presents another opportunity to leverage sugarcane feedstocks, offering competitive pricing in line with HEFA.

On the one hand, despite HEFA being superior in terms of its low CAPEX, feedstock costs significantly affect the MJSP, underscoring the importance of securing cost-effective, sustainable feedstock supplies. This could remain a challenge for HEFA when prices of vegetable oils fluctuate, as seen in the past. Energy crop production focusing on rural development, job creation and environmental management as co-benefits of SAF production will help secure broader stakeholder support and align national policy goals to meet the demand for feedstock.

On the other hand, to tap into the advantage of low feedstock prices for FT, governments need to provide strong incentives to encourage private investment, particularly in the early stages of FT plants' deployment. Developing financial mechanisms to reduce the burden of pioneer plant CAPEX, fostering public-private partnerships and promoting regional co-operation on SAF supply chains will be essential.

ICAO has provided a few examples of policy options that can be implemented to stimulate the growth of SAF supply (ICAO, 2023). One such option is targeted incentives and tax relief to support SAF supply infrastructure. For example, a government grant could be provided to an entity to build or purchase SAF-specific infrastructure, including production facilities, transportation networks, refuelling stations or blending infrastructure. Capital grants can help reduce the financial burden and risks associated with these investments. Alternatively, a government-backed loan could strengthen the project's financial case by lowering overall project risk, making it easier to secure additional equity or debt and reducing the cost of capital. Another option is granting SAF projects a tax-advantaged status, which exempts them from certain fiscal obligations.

2.5 KEY FINDINGS

- SAF is not yet cost-competitive. Its production costs vary significantly across Southeast Asia, with Malaysia showing the highest CAPEX among the three selected countries, particularly for FT pathways, and Indonesia having much lower costs due to PPP.
- HEFA technology consistently demonstrates the lowest CAPEX, making it a viable option for early stage SAF development.
- Securing cost-effective and sustainable feedstock supplies for HEFA pathways is crucial, as fluctuating vegetable oil prices can greatly impact the MJSP. Energy crop production that generates co-benefits for rural development, job creation and environmental management can be aligned with national goals and create broader stakeholder support.
- While FT plants could become competitive at the n^{th} plant stage, high initial investment costs require substantial financial support, incentives and policy interventions to overcome these barriers.
- To jumpstart large-scale FT plant deployment, governments will have to develop financial mechanisms to reduce the burden of pioneer plant CAPEX, foster public-private partnerships and promote regional co-operation on SAF supply chains.

3. REGIONAL PERSPECTIVES

3.1 SCOPE

The relevance of and readiness for SAF production vary across countries in Southeast Asia, reflecting differences in feedstock availability, technological capabilities, infrastructure, market conditions and potential demand. Analysing these factors provides valuable insights into each country's position within the growing SAF industry. This comparison considers the progress of SAF production pathways, evaluating the influence of government policies, industry advancements and research initiatives. Understanding these elements is key to assessing the potential for SAF adoption and development across the region.

In Southeast Asia, SAF development varies widely by country. Singapore, Malaysia, Indonesia, Thailand and the Philippines are regarded as early adopters, while others remain potential prospects. Indonesia, Malaysia and Singapore have each launched SAF blueprints or road maps, with plans to introduce mandates in the coming years. Notably, Singapore is the first to establish a mandate. Meanwhile, the Philippines and Thailand are currently developing their national road maps for SAF development. Table 5 summarises the current status of policy development.

Table 5 Current status of policy development

COUNTRY	MANDATE	SAF ROAD MAP/BLUEPRINT
Singapore	To be implemented, 1% in 2026	Launched in 2024: (www.caas.gov.sg/docs/default-source/docs---so/singapore-sustainable-air-hub-blueprint.pdf)
Malaysia	Planned	Launched in 2024: (www.mot.gov.my/en/Pages/Aviation/MADBlueprint BI FA.pdf)
Indonesia	Planned	Launched in 2024: (https://maritim.go.id/pdf/peta-jalan-pengembangan-industri-sustainable-aviation-fuel-saf-indonesia#book/)
Thailand	In progress	SAF development to be included in the latest "Thai Oil Plan", which is still in progress at the time of writing: (www.bangkokpost.com/business/general/2716601/national-oil-plan-to-promote-sustainable-fuel)
The Philippines	In progress	In progress
Rest of Southeast Asia	N/A	No policies

This chapter explores the current status of these early adopters, including ongoing and planned projects, as well as relevant policies addressing both the supply of and demand for SAF. Strategies for countries are discussed, drawing results from previous chapters, lessons learned from various SAF and biofuel projects, and stakeholder input gathered through interviews and group discussions.

3.2 MATERIALS AND METHODS

In addition to desktop analysis, group discussions and interviews were conducted with stakeholders from Indonesia, Malaysia, the Philippines, Singapore and Thailand in September-October 2024. Prior to the stakeholder consultation sessions with the respective countries, the attendees were given a set of questionnaires along with an introductory deck of slides. Additional anecdotal information was gathered through informal engagements with stakeholders, supported by information retrieved from publicly available documents, presentations, news and other sources throughout 2024. These findings were cross-checked with the results from chapters 1 and 2.

3.3 GLOBAL DEVELOPMENT AND IMPLICATIONS FOR SOUTHEAST ASIA

The development of SAF is driven largely by the commitments declared by the aviation industry and governmental bodies with the CORSIA initiatives under ICAO. CORSIA is the first global measure for emissions reductions among all sectors, achieved through a co-operative approach with industry, airlines and government (Prussi *et al.*, 2021). As of 1 January 2024, CORSIA had a total of 126 states participating, representing over 85% of global aviation traffic (CORSIA, n.d.).

The focus of the industry's decarbonisation effort is the usage of SAF, due to SAF's capacity to reduce emissions by up to 80% on average during its lifecycle. However, the SAF industry is still in its infancy, with a current global production capacity of less than 1% of global aviation fuel usage. IATA estimates that

SAF production by the end of 2024 will be 1.5 Mt (1.9 billion litres), or 0.53% of global aviation fuel needs (IATA, 2024). Globally, it is estimated that 330 Mt of SAF will be required around the world by 2050.

To realise mass production of SAF, a more holistic approach towards regulation and policy development is required. Developing the entire SAF ecosystem is incredibly challenging, involving actors from the land sectors (feedstock producers and processors), feedstock collectors and traders, downstream processors (bio-based industry and fuel industry), as well as retailers and off-takers (airports, airlines). The situation will be even more complex with international trade of feedstock and SAF as described in Chapter 1.

Globally, countries are implementing, and looking to implement, various policies and regulations to advocate and promote the use of SAF as part of the commitment to decarbonise the aviation sector. For the most part, global policies and their implementation are still highly fragmented and for most of the world, absent. CORSIA has provided a good baseline for policy makers and regulators to initiate the discussion across all levels of government and industry, but this takes time, effort and co-operation. To simplify implementation, progress can be recognised in four key areas, as shown in Figure 7: 1) overall regulation for SAF in the country; 2) SAF demand; 3) SAF supply; and 4) feedstock supply.

Figure 7 Progress of SAF development in different regions

	REGULATION	DEMAND	SUPPLY	FEEDSTOCK
Europe	✓	✗	✗	✓
United States	✓	✓	✗	✓
Canada	✗	✗	✗	✓
Asia-Pacific	✗	✗	✗	✓
China	✗	✗	✗	✓
South Asia	✗	✗	✓	✓
Latin America	✗	✗	✗	✓
Africa & Middle East	✗	✗	✗	✗

✓ Beyond industry ambition ✓ In line with ambition ✗ Lagging vs. ambition

Based on: (International Transport Forum, 2023; Le Moing, 2024).

Currently, the United States and Europe are the pioneers in SAF regulation. The situation in the United States is different to that in Europe due to the difference in perceptions regarding how best to nurture and encourage SAF adoption. The United States takes a position of advocating incentives to the ecosystem including energy crops production, while Europe takes a position of mandate implementation. To the south, Latin America has aligned the region's ambition for SAF with its advantages in feedstock supply, *i.e.* its capacity to produce bioethanol from its massive sugarcane industry (especially in Brazil) (IRENA, 2024). Most regions have yet to consolidate their SAF demand and supply. The situation becomes particularly complex when international trade of feedstocks, such as UCO, significantly impacts feedstock availability across different locations. Caution has to be taken as the fragmentation in regulating the SAF ecosystem is still considerable.

While there is theoretically enough feedstock and land to meet the demand for SAF, the **uneven geographic distribution of feedstocks versus mandates** presents significant challenges to SAF deployment. This issue is particularly relevant for Southeast Asia, where feedstock availability is both a strength and a vulnerability. Historically, Southeast Asia has been a key supplier of bio-based feedstocks to other regions, such as UCO exports to China and wood pellets to Japan, Korea and more recently the European Union. A similar trend could emerge in the SAF market, where accessible feedstocks – especially UCO – are siphoned off to meet external demand (see Chapter 1). Within the region, Singapore, with its strong SAF policies and industrial infrastructure, may further attract a disproportionate share of available feedstocks. The potential competition for feedstocks limits the resources available for Southeast Asian countries to develop their SAF industries.

Sustainability remains central to the global development of SAF. Beyond GHG savings, traceability is key to ensuring the eligibility of feedstocks, covering broader aspects such as water usage, soil and air pollution, land use rights, human and labour rights, local and social development, and food security impacts. As SAF regulations mature, particularly concerning feedstocks, the current supply landscape may shift as the industry moves from merely sourcing feedstock to enforcing strict governance and traceability from feedstock to fuel tank. One important factor is feedstock classification, particularly for commodities derived from the palm oil industry. Only a few palm oil-based feedstocks, such as EFB, PFAD, fresh fruit bunches (FFBs) and POME oil, are currently approved as CEFs (ISCC, 2023). Although this list may evolve, certain feedstocks face more scrutiny, with palm oil-derived products being particularly criticised, especially by the European Union. Indonesia and Malaysia, the world's leading palm oil producers, have protested against this, arguing that they are unfairly disadvantaged. The sustainability challenge is especially critical for Southeast Asia, as energy crop cultivation may become an increasingly necessary component of future SAF production. Balancing these sustainability concerns with the growing demand for feedstocks will be a key issue for the region moving forward.

The ICAO's CORSIA initiative has been exploring the introduction of a **"book and claim" system** to address the challenges in global SAF distribution (ICAO, n.d.b). This system operates under the "chain of custody" principle, enabling SAF purchases to be separated from geographic and supply chain constraints. It provides a flexible solution for buyers, granting them access to SAF's emission savings without requiring physical fuel transport or the need for local SAF infrastructure. In practice, an airline can use SAF without claiming the emissions savings, while another airline, possibly located far away where SAF is either unavailable or too costly, can claim those reductions. This system stimulates the SAF industry by aggregating global demand, creating opportunities for producers and feedstock suppliers to meet growing market needs, and allowing countries and companies to participate in SAF adoption without necessarily producing or storing it locally.

For Southeast Asian countries that require more years to get ready for SAF mandates (considering the price impacts on local passengers), the "book and claim" system presents an opportunity to jumpstart their SAF industries. Countries rich in feedstocks but not ready for SAF mandates – or that have low air traffic (such as Cambodia and Lao PDR) – could still produce SAF and participate in the market. They would do this by selling sustainability credits to airlines in other countries or regions (such as Singapore and Japan), without the need for transporting SAF physically to other regions while creating an initial revenue stream that can support future industry growth. Over time, as these countries develop their own SAF ecosystems, they may be better positioned to use SAF for their own decarbonisation targets. However, the "book and claim" system is still under development, and thus the benefit from this system remains uncertain in the near term (ICAO, n.d.b).

3.4 COUNTRY STATUS AND PERSPECTIVES

Singapore: The first mover and the largest off-taker

Singapore has emerged as a pioneer in Southeast Asia when it comes to SAF adoption, demonstrating both policy commitment and strategic industrial planning. Singapore is the region's largest aviation fuel consumer (more than 5 Mt of fuel per year) and has a central geographical location in the Asia-Pacific region. These elements, together with Changi Airport's growth plans, make Singapore a favourable location for investors.

The Civil Aviation Authority of Singapore (CAAS) launched the Sustainable Air Hub Blueprint in February 2024 as the city-state's comprehensive action plan to reach net-zero aviation emissions by 2050. In early 2024, the country introduced its SAF mandate, the first in Southeast Asia. The mandate aims for an initial SAF uptake of 1% by 2026, with plans to scale up to 3-5% by 2030, depending on SAF availability and market conditions

(Civil Aviation Authority of Singapore, 2024). To facilitate this transition, the CAAS will centrally procure SAF, with costs funded through levies on air travellers. These levies will vary based on distance travelled and class of service, adding a small surcharge of around USD 2-12 to the ticket prices of economy passengers on key routes like Singapore to Bangkok, Tokyo and London. While the SAF levy will remain constant regardless of fluctuations in SAF prices, the actual volume of SAF procured may be adjusted based on market prices and the pre-determined levy amounts, providing financial stability for both airlines and passengers.

The country is further cementing its leadership in sustainable aviation through international partnerships, such as a memorandum of understanding (MoU) signed with Airbus. This MoU aims to establish a sustainable aviation hub in Singapore, focusing on cutting-edge technology, research and innovation to accelerate the transition to SAF. Singapore's proactive measures highlight its ambition to create an ecosystem that reinforces its status as a major aviation hub (AIRBUS, 2024).

The expansion of Neste's Singapore refinery in 2024 marks a significant milestone in Southeast Asia's SAF development (Amsen, 2024). The upgrade, which doubles the refinery's production capacity from 1.3Mt/yr to 2.6 Mt/yr, enhances the availability of SAF, renewable diesel, and raw materials for polymers and chemicals. With this expansion, Neste's global SAF production capacity now reaches 1 Mt annually. Singapore Airlines (SIA) and Scoot are the first airlines to use SAF produced at Neste's Singapore refinery through an agreement for the purchase of 1000 t in 2024. SIA's goal is higher. This agreement supports SIA Group's goal of achieving at least 5% SAF in its total fuel usage by 2030.

A critical challenge facing Singapore's ambition lies in feedstock availability. Recently, China and Indonesia both saw record exports of UCO to Singapore, noting that it could be due to Neste's refinery in Singapore (Oils & Fats International Magazine, 2023; Quantum Commodity Intelligence, 2023). However, caution will have to be taken as UCO exporters, such as China, will need to mature their own SAF ecosystem and may restrict the export of SAF feedstock to prioritise their own country's development of SAF (Li *et al.*, 2024). Within the region, feedstock from residues and wastes is spread unevenly, as detailed in the analysis in Chapter 1. Countries such as Malaysia, Thailand and the Philippines are projected to face significant feedstock shortages by 2050, with their local supplies falling short of the demand needed to fully decarbonise their aviation sectors. While Indonesia possesses a substantial amount of feedstock, these resources are primarily in the form of solid biomass spread across its vast territories. The practicality of mobilising these resources for SAF production in Singapore is highly questionable, as much of this feedstock is bulky and costly to transport over long distances.

Additionally, diverting these resources to Singapore could create a vacuum in the region, depriving other countries of critical feedstock needed for their own decarbonisation efforts. If Singapore focuses on sourcing feedstock from readily available waste oils like UCO and POME oil from the region, it risks merely shifting the problem elsewhere rather than contributing to meaningful emissions reductions. This strategy could hinder regional efforts to decarbonise, as it would pull resources away from countries struggling to meet their own SAF production targets, resulting in a fragmented approach to climate action.

These concerns raise important questions about the sustainability and feasibility of relying on regional biomass supplies to fuel Singapore's SAF ambitions. The country may need to explore alternative solutions, such as co-creating regional value chains and investing in energy crop cultivation, carefully accounting for the different stages of SAF adoption in the neighbouring countries, as well as various sustainability considerations in local and regional contexts. Only an approach that focuses on generating sufficient new feedstock for the entire region by 2050, rather than depleting existing resources, will enable Singapore to maintain its leading role in the SAF industry. A regional collaboration framework is necessary to ensure Singapore's access to a broader range of sustainable feedstock options, supporting the growth and stability of SAF production in the region.

Malaysia: Most announced and planned projects

Malaysia is positioning itself as a key player in the regional SAF market, with a notable number of announced and planned projects. The country currently has at least eight active players involved in refinery construction and feedstock development, more than any other country in the region. Malaysia's early efforts in SAF can be traced back to 2014, when the Aerospace Malaysia Innovation Centre, in collaboration with Airbus and the Malaysian government, launched the country's first SAF project. This initiative explored the potential of local feedstocks for SAF, laying the groundwork for future developments even before the global adoption of CORSIA (Green Air, 2014).

These early initiatives have since been integrated into Malaysia's broader strategic frameworks. SAF development is included in Malaysia's Twelfth Malaysia Plan (2021-2025), which emphasises the country's commitment to sustainable aviation fuel (EPU, 2021). Additionally, Malaysia's National Energy Transition Roadmap (NETR) identifies "Green Mobility – Aviation" as a key initiative. This includes the collaborative decarbonisation of the aviation sector, the introduction of an SAF blending mandate targeting 1% (though the timeline remains unspecified, with a long-term target up to 47% SAF blending by 2050), and a study to reassess palm oil feedstock emissions and the indirect land use change impact, aiming to promote the use of palm oil for SAF production (Ministry of Economy, 2023).

In September 2024, the Malaysian government unveiled its first comprehensive aviation industry carbon reduction plan, the Malaysia Aviation Decarbonisation Blueprint (MADB) (Ministry of Transport Malaysia, 2024). The MADB outlines four key carbon reduction strategies for airlines, with SAF holding the highest estimated contribution to emissions reduction at 46% by 2050. Notably, this number is lower than the global target of 65% set by IATA. This is because the country sees carbon credits as an important element to

decarbonise the sector, potentially offsetting 31% of the sector's emissions, complemented by advancements in aviation technology (18%) and operational efficiency (5%).

With Malaysia's dual approach (SAF and carbon credits), the government has yet to announce a mandate for the use of SAF in Malaysia. This is mainly due to its acknowledgement of the supply-side constraints, which are crucial to assess properly before airlines can adopt SAF at scale. Despite the progress, alignment in SAF policies in Malaysia is still needed between the various plans and policies. The MADB is the latest document and is the current guide for Malaysia in the aviation sector's decarbonisation goal, while the NETR 1% SAF blend is a target for Malaysia to develop towards before committing to a further blending rate. However, because the various policy documents were developed by different ministries, these initiatives differ in targets and stages of implementation. Harmonisation is required to accelerate the country's progress in SAF development and motivation towards higher blending targets.

Amid the uncertainties, the national oil company, Petronas, has pledged to start producing SAF by as early as 2028 to meet the expected demand. The government expects this development to lower SAF costs, which are currently triple that of conventional jet fuel. The country's readiness in this sector is underpinned by several factors, including abundant feedstock resources, established biofuel infrastructure, government support and international partnerships.

The country's abundant agricultural resources, available in various forms, are seen as potential feedstocks for SAF. However, key initiatives and investments are mainly based on HEFA. EcoCeres Renewable Fuels has invested USD 230 million in Johor, which is set to begin production in 2025 (MIDA, 2023). In addition, LOKEN has announced its plan to establish the first commercial-scale HEFA plant in the country by 2025 (FocusM, 2023).

The national airline, Malaysia Airlines, flew its first cargo and passenger flights with NESTE's SAF (supplied by Petronas) in 2021 and 2022. It subsequently had an offtake agreement with Petronas in 2023 to supply over 230 000 t of SAF to the Malaysian Aviation Group (covering Malaysia Airlines, Firefly and MASWing divisions) in 2027/2028 (Malaysia Airlines, 2021, 2022; Reuters, 2023). AirAsia Group, with its headquarters in Malaysia, has a considerable footprint in ASEAN and has partnered with Airbus to establish a collaboration to explore decentralised production of SAF in the Southeast Asia region (AirAsia, 2024). These two airline operators account for the majority of the country's aviation fuel consumption.

However, as depicted in Chapter 1, Malaysia will not be able to meet the SAF demand at 70% blend with its existing residues and wastes. Even if the target is set at 46% as in the MADB, the country still needs additional feedstocks from energy crop cultivation. The planned HEFA facilities in Malaysia, valued at around USD 3 billion and with a total capacity of 1.5 Mt/yr, will rely on imports when fully operational (Bernama, 2021; Biofuels International, 2023; MIDA, 2023; Moffitt, 2021; Neste Corporation, 2023; PETRONAS, 2024). Interestingly, Petronas has been looking into microalgal oil as another feedstock of interest. It has partnered with Eni and Euglena to develop a biorefinery in Johor, Malaysia that will produce renewable diesel and SAF, targeted to be operational by the second half of 2028, using various raw materials, including microalgae oils (Petronas, 2022). The state of Sarawak also unveiled plans to construct a bio-refinery in Bintulu, focusing on SAF production, using locally cultivated microalgae oil as feedstock (Kentigern Minggu, 2024).

Currently, without a mandate, foreign investment might aim to position Malaysia as a key feedstock supplier for SAF-hungry markets like Japan and Singapore. This approach could exacerbate supply-demand imbalances if the targets outlined in the MADB are to be met. In the long term, a phased strategy may be needed to provide clearer direction for SAF development, with the initial focus on establishing a comprehensive SAF ecosystem that supports both local consumption and international trade. Subsequently, Malaysia should gradually invest in energy crop cultivation to fulfil domestic targets and enhance export revenue.

Indonesia: Perspectives as the largest palm oil producer

In 2019, Indonesia recorded a Kerosene Jet A-1 fuel consumption of 3.9 Mt (close to 5 billion litres), with demand projected to grow to 5.1 Mt by 2030. Despite being the world's fourth most populous country, Indonesia currently ranks only 23rd in aviation fuel consumption. However, Indonesia's demand is expected to grow significantly due to the country's rapid economic development and the government's plan to decentralise economic activities across the islands, including the relocation of the capital from Java to Kalimantan.

With its vast feedstock potential, Indonesia has the opportunity to emerge not only as the leading SAF producer in Southeast Asia but also as a major global player in the industry. The analysis in previous chapters highlighted that Indonesia not only holds the highest potential for SAF feedstock availability but also benefits from relatively low CAPEX for SAF manufacturing. In September 2024, Indonesia unveiled a SAF road map and policy action plan, set to be implemented through a Presidential Instruction (Giam, 2024). Broadly, the 2025-29 SAF Action Plan is structured around three key pillars: supply, demand and enablers.

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Under the supply pillar, the government aims to secure domestic feedstocks for SAF production, focusing on the HEFA pathway. This includes a proposed domestic market obligation for PFAD, alongside potential export quotas or tariffs for UCO. Emission-based incentives and exploration of alternative production pathways, such as ATJ, were also outlined. While UCO and PFAD are prioritised as feedstocks, the government anticipates using palm oil as well, claiming that there is already an excess supply of 16.5 Mt, which could yield 13.3 Mt of SAF. The stakeholder consultation revealed that palm oil was chosen as a feedstock for SAF based on a scoring system used by Indonesia's Ministry of Energy, which considers factors like supply availability, environmental performance, technology readiness and alternative uses. However, the system does not set thresholds for emission reductions.

To date, SAF derived from palm oil is not included in the standards set by CORSIA, the United States or the European Union due to environmental concerns, limiting its global market potential. Indonesia plans to form a task force to engage with ICAO over the next two years to push for the eligibility of palm oil for SAF production. In this regard, Pertamina, Indonesia's state-owned energy company, has been given the task to lead efforts in this space. It pioneered the production of Bioavtur J2.4, a biofuel blend containing 2.4% palm oil, and has successfully conducted flight tests in partnership with Garuda Indonesia. Pertamina's Cilacap refinery has the capacity to produce 1 350 kilolitres of SAF per day, mainly using palm kernel oil (Isaac, 2023).

Discussions around cultivating energy crops like Pongamia on under-utilised low-carbon land for biofuel production have been ongoing for decades. However, there are still no significant projects being implemented in the country. As highlighted in Chapter 1, a key challenge is the persistent labour shortage, as much of this low-carbon land is in sparsely populated areas such as Kalimantan. Anecdotal sources suggest that Japan and Singapore have shown interest in investing in SAF manufacturing in Indonesia. Discussions are underway among government agencies to promote the establishment of a special economic zone dedicated to SAF and biofuel production. The goal is to elevate this initiative to a national strategic programme to access both fiscal and non-fiscal incentives.

Under the enablers and demand pillar, international flights departing Indonesia are targeted to use 1% SAF by 2027, increasing to 30% by 2050 and 50% by 2060 (Giam, 2024). Indonesia plans to develop a national SAF certification system and to initiate pilot SAF offtake agreements at major airports, starting with Ngurah Rai International Airport and Soekarno-Hatta Airport. Additionally, there are plans to introduce SAF usage mandates for corporate and government travellers (Giam, 2024).

Thailand: Sugar for food and/or fuel

While Thailand has a long history of bioethanol production from sugarcane, currently the key initiatives for SAF focus mainly on UCO. The Bangchak Group's "Fried to Fly" campaign and the "Thod Mai Throw" project aim to collect UCO from households and businesses to supply the country's first SAF facility, which is under construction and scheduled to be operational by early 2025 (Bangchak, 2024). A significant portion of this SAF will be exported to Japan under a ten-year agreement with Cosmo Oil (Hussain, 2024), underscoring an export-driven strategy common in Southeast Asia due to the region's still-developing SAF policies and mandates.

As discussed in Chapter 1, Thailand's future SAF demand – especially by 2050 – will likely exceed what can be met using only residues and waste, particularly considering the competition for exports and other uses. Some of the existing uses are not recorded in statistics or literature, making it difficult to justify the feedstock availability for SAF. For example, rice husks may have already been widely used as bedding materials for chicken farms. However, stakeholder consultations have pointed out that Thailand has yet to explore the potential of energy crops on under-utilised low-carbon land. While FAOSTAT data suggest there could be millions of hectares of non-forested, non-agricultural land available, there are no spatially explicit or provincial-level data to guide land-use planning, leaving the government without a clear strategy in this area.

If energy crops were to be considered, sugar crops like sugarcane and cassava are likely to play a key role. Chapter 2's techno-economic analysis reveals that SAF production via the ATJ pathway using first-generation sugar feedstock has lower CAPEX compared to FT synthesis. Thailand's experience with sugar-based bioethanol in past decades highlights both opportunities and challenges for SAF production. As global demand for aviation fuel rises, ethanol prices are likely to increase, incentivising producers to prioritise ethanol over sugar, potentially driving up global sugar prices (Carpio, 2019). This scenario illustrates the complexity of balancing agricultural resources for energy and food. This is further complicated by Thailand's governance structure, where multiple ministries, including transportation, environment and resources, agriculture, energy, and foreign affairs are involved in SAF development, often slowing progress. Currently, SAF matters are placed under the National Committee of Climate Change led by the prime minister.

On the demand side, as with other countries in the region, Thailand's policy making for SAF remains reactive to market signals, although the country has plans for climate targets by 2050. While there are no specific subsidies for SAF blending, incentives are provided for upstream activities to stimulate industrial development. These include a range of fiscal and non-fiscal incentives within special economic zones, targeting bio-based industries, including SAF production.

The Philippines: Potential from non-standard coconuts

The Philippines is considered one of the early adopters, as the country has already initiated the planning process for SAF deployment. The government, through various agencies like the Civil Aviation Authority of the Philippines and the Department of Energy, is gradually building policies to support SAF adoption, mainly placed under the provision of National Biofuel Board (Department of Energy, 2011). While SAF is technically considered and covered by the Renewable Energy Act as well as the Biofuels Act of 2006, a development road map was still under development at the time of writing (United States Department of Agriculture, 2023).

On the production side, Prime Infrastructure Capital has launched a waste-to-fuel project in partnership with United States-based WasteFuel Global. It plans to build a biorefinery in the Philippines to convert 1 Mt of municipal waste into over 110 million litres of SAF annually while addressing the country's waste management issues. This USD 600 million project, which is expected to significantly reduce landfill emissions and environmental hazards, has attracted a 380 million litre SAF purchase commitment from private aviation leader NetJets over the next decade (Bacosa, 2021). However, no updates have been made publicly available since the first announcement in 2021.

On the consumption side, the private sector has taken the initiative in collaboration with international stakeholders. Cebu Pacific, the country's largest low-cost airline, began using SAF in 2022 and now incorporates it into its fleet. In partnership with Shell Eastern Petroleum, Cebu Pacific signed an MoU to expand SAF availability in the Asia Pacific and the Middle East, aiming to launch "green routes" within the next few years. Philippine Airlines, the national carrier, is also working on incorporating SAF into its operations. Additionally, the Bank of the Philippine Islands has adopted DHL's GoGreen Plus Service, which uses SAF to reduce the bank's annual GHG emissions from shipping documents by 90%, further highlighting the growing SAF momentum in the country (United States Department of Agriculture, 2023).

An opportunity for the Philippines could be its well-established coconut industry. As the world's second-largest coconut producer after Indonesia, the country holds significant potential for SAF production through the use of non-standard coconuts. These coconuts, which are sprouted, too small, cracked or otherwise unsuitable for human consumption, have been recognised by ICAO as a CORSIA-eligible feedstock since

March 2024. Assuming that approximately 30% of the Philippines' annual coconut production could potentially qualify as non-standard, as estimated in Box 2, the country's SAF production could potentially increase by 0.6 Mt annually. As the Philippine government develops its SAF road map and builds supportive policies, integrating coconuts into SAF production could bolster both the country's coconut industry and its decarbonisation efforts.

3.5 DISCUSSION

This chapter has highlighted the different stages of SAF development among the Southeast Asian countries, as well as the uneven distribution of feedstock and demand in the region. The first mover, Singapore, depends on regional feedstocks from neighbouring countries. This situation could create a complex trade ecosystem and lead to unwanted competition for resources, potentially hindering other countries from achieving their targets.

Beyond the region, countries such as Japan and Australia, which are not major feedstock producers, may seek to secure SAF supplies from Southeast Asia, increasing competition for feedstock and potentially raising prices. Japan has already partnered with Thailand and Malaysia in SAF development projects, signalling its growing interest in the region's resources. Japan's agreement with Thailand's Bangchak Corporation, for instance, involves a ten-year import deal for SAF. Similarly, Singapore's agreement with Cosmo Oil in Japan for SAF imports further solidifies the trade interdependence in the region.

Nevertheless, extra-regional investments play a critical role. In the Philippines, Prime Infrastructure Capital's partnership with United States-based WasteFuel Global highlights the growing trend of international investments in SAF projects. Such collaborations not only contribute to SAF production but also address pressing waste management issues. Additionally, NetJets' long-term purchase commitment from the Philippines underscores the growing demand for SAF from global aviation players. These international partnerships are critical for smaller producers like the Philippines, which have significant feedstock potential such as non-standard coconuts, but require foreign investment to scale production.

While Southeast Asia's potential for SAF production is substantial, the environmental sustainability of feedstocks like palm oil remains an important aspect. Indonesia's reliance on palm oil for SAF production in particular raises questions over sustainability. Notably, stakeholder feedback indicates that the Philippines, through its National Biofuels Board, is actively exploring the potential of using palm oil as a feedstock for SAF. In any case, to ensure the environmental benefits of SAF, growing energy crops on under-utilised low-carbon land will have to be done carefully. Malaysia is leading in this aspect, as the country has begun exploring the cultivation and the use of microalgae for SAF. Petronas, in partnership with Eni and Euglena, is spearheading the development of a biorefinery that will utilise microalgae to produce SAF. Indonesia has also discussed cultivating Pongamia on low-carbon under-utilised land for biofuel production.

From a social perspective, the development of energy crops in rural areas could stimulate economic growth and job creation. However, persistent labour shortages in remote areas, such as Kalimantan in Indonesia, could impede the scalability of SAF production and require substantial investment in infrastructure and labour development.

Southeast Asia is poised to become a major player in the global SAF market, but its success will depend on a delicate balance of intra-regional trade, energy crop development and co-operation with extra-regional partners. In general, countries in Southeast Asia tend to be more reactive than proactive in their approach to SAF development. During consultation sessions, a government representative highlighted that policy decisions are often driven by market signals rather than a strong commitment to decarbonisation. As discussed in Chapter 1, the region is unlikely to meet the SAF volume required for full decarbonisation if it relies solely on residues and waste, due to stiff competition for these resources and challenges in mobilisation. While the cultivation of energy crops will likely be necessary to meet SAF demand, establishing these crops at the required scale could take decades. Despite this, most countries have yet to develop comprehensive plans to explore or invest in large-scale energy crop cultivation.

Given the complexities of domestic production, regional trade and extra-regional demand, the development of **a co-ordinated regional framework for SAF production and trade** would be beneficial. This proactive approach should focus on creating regional feedstock value chains, where countries collaborate strategically to ensure a balanced distribution of resources. As discussed in earlier chapters, several countries have the potential to become net SAF exporters or, at the very least, to export sustainable feedstock to support neighbouring nations while maintaining sufficient resources to meet their aviation growth needs. For example, countries could pool feedstock resources, with cross-border investments boosting regional production capacity. Moving forward, the region might consider implementing a "book and claim" system to stimulate SAF production across all nations, enabling countries to meet their SAF targets at their own pace. Additionally, a sustainability framework could foster deeper co-operation on feedstock sourcing and policy alignment. A regional SAF certification system could standardise production practices, ensuring compliance with international sustainability standards, particularly given concerns about palm oil-based SAF.

If the ASEAN region were to establish **a regional SAF working group** and collaborate among neighbouring countries, it could create a synergistic effect that stabilises and mitigates risks, while also offering a financial advantage compared to regions like the European Union. Notably, the high intra-regional traffic (36%) (ASEAN Stats Data Portal, n.d.) further strengthens the need for a regional aviation decarbonisation framework. Regional collaboration is not new to ASEAN, as demonstrated by the implementation of the ASEAN Single Aviation Market (ASEAN-SAM) over the past decade (Box 4). However, challenges remain in its execution due to ongoing disagreements between member states, and similar issues could arise in the development of SAF. To overcome these hurdles, fostering open dialogue and building consensus through shared goals will be essential, ensuring all nations benefit from a unified approach.

Additionally, **collaboration with extra-regional players**, including investments from Australia, China and Japan, will be crucial for driving SAF development in Southeast Asia by bringing necessary capital and technological advancements. Such partnerships could help build an integrated SAF ecosystem that supports regional decarbonisation while contributing to global climate objectives. A co-ordinated strategy, both intra-regional and with neighbouring regions, could accelerate SAF adoption and bolster regional sustainability efforts. In 2023, ASEAN officially adopted the ASEAN Sustainable Aviation Action Plan to share best practices on aviation decarbonisation, facilitate information exchange and collaborate on developing an ASEAN Sustainable Aviation Roadmap (ASEAN, 2023). This will be a key platform for the countries to establish collective aspirational SAF goals for the region, outline pathways to enhance regional SAF production and adoption, and align efforts with ICAO's LTAG.

Box 4 The ASEAN-SAM

The ASEAN-SAM, also known as the ASEAN Open Sky Agreement, is a major aviation policy aimed at creating a unified air transport market among ASEAN member states (ICAO, n.d.c). It was proposed to liberalise air travel across the region, fostering growth in tourism, trade, investment and services by allowing airlines from member countries to operate freely within ASEAN. The Open Skies policy aims to improve regional connectivity and trade by allowing airlines to operate across member states without many of the previous restrictions. It aims to advantage the region by enabling it to negotiate aviation agreements with major international partners – such as the European Union, the United States, China, India and others – as a block. The policy was intended to take effect by 1 January 2015, although not all agreements were finalised at that time. Progress toward full implementation has since then been uneven, with some countries delaying ratification or imposing restrictions, including Indonesia, Lao PDR and the Philippines (Meszaros, 2016).

3.6 KEY FINDINGS

- Progress in SAF development across Southeast Asia varies, with notable advancements in Singapore, followed by Malaysia, Indonesia, Thailand and the Philippines. The uneven distribution of feedstock and differing stages of policy development may hinder countries' ability to meet SAF targets.
- On the demand side, most Southeast Asian countries tend to be reactive to market signals rather than proactive. To date, no subsidies or other direct incentives are provided or are planned to be provided. Instead, adoption is driven by mandates, which are funded by traveller surcharges that vary by route and class.
- On the supply side, SAF production is supported as part of industrial development, with fiscal and non-fiscal incentives given to attract investment. However, policy making and implementation are slowed by the involvement of multiple ministries, which may include agriculture, transport, industry, energy, foreign affairs and local governments.
- Countries like Australia, China and Japan are increasingly partnering with Southeast Asian nations like Malaysia, the Philippines and Thailand for SAF production, mainly focusing on export-oriented models. While such models may intensify feedstock competition, foreign investment is essential to provide critical capital and technology.
- Ensuring feedstock sustainability will be critical as energy crops are needed. Indonesia's reliance on palm oil raises concerns, while potential feedstocks like microalgae and non-standard coconuts provide interesting alternatives.
- A co-ordinated regional framework for SAF production and trade could help balance competition and foster sustainability. Implementing a "book & claim" system may offer flexibility in meeting SAF targets and scaling production across countries at different stages of development.

4. RECOMMENDATIONS

This study brings together the insights essential for unlocking Southeast Asia's potential as a key player in SAF development. While the region holds immense promise due to its abundant bio-based resources, expanding aviation sector, and governments eager to drive sustainable growth, realising this potential is far from straightforward. The challenges include uneven access to feedstock, varying levels of policy development, and the complexity of managing cross-border trade and investment, among others. These underscore the need for co-ordinated action and strategic planning at both national and regional levels to navigate the dynamic landscape of SAF development.

What becomes clear is that Southeast Asia must not only scale up SAF production to meet its own growing aviation demands but also position itself as a key contributor in the global supply chain. Doing so will require a delicate balancing act between fostering economic growth and ensuring environmental sustainability, and between national targets and regional partnerships. Below are recommendations for governments, industry leaders and stakeholders to prepare and formulate practical strategies for securing the region's role in decarbonising global aviation in two major domains.

(A) A CROSS-SECTORIAL FRAMEWORK FOR SAF DEVELOPMENT

SAF development must be integrated into a wider framework that considers feedstock availability, energy security and economic development across multiple sectors. Achieving this will require comprehensive planning, co-ordination between industries and a strong focus on sustainability in tandem with broader bio-based and nature-based economies. This includes the need for consistent and sustainable feedstock supplies, improved policy co-ordination and careful allocation of resources.

1. **Establish reliable and consistent supplies of residues and waste as SAF feedstock**
    - Formulate feedstock sourcing business models based on sectorial and local contexts, especially existing industrial practices and local preferences in the agricultural and forestry sectors.
    - Support logistics and infrastructure improvements to optimise the collection, transport and conversion of residues and wastes.
    - Encourage technology transfer agreements with foreign partners to ensure that Southeast Asian countries benefit from foreign expertise and are not solely reliant on exporting feedstock or SAF.

2. **Establish clear guidelines for energy crop cultivation**
    - Identify under-utilised low-carbon land suitable for energy crop cultivation with comprehensive methodologies considering social and environmental factors.
    - Invest in research and development of alternative feedstocks like microalgae, non-standard coconuts and other innovative biomass sources.
    - Integrate energy crops in land-use planning through a landscape approach to secure food and energy production, carbon and biodiversity conservation, and socio-economic importance.
    - Link SAF development to environmental restoration, conservation and climate goals.
    - Harmonise and reinforce land-use sustainability requirement across sectors.

3. **Reassess feedstock allocation for different end uses**
    - SAF development needs to be carefully incorporated into the national energy transition road map, ensuring consistent policies across ministries and sectors.
    - Reassess feedstock allocation strategies over a longer time frame, with special attention given to hard-to-abate sectors like aviation and shipping, which have fewer alternatives for decarbonisation.
    - Incentivise the use of alternatives in other sectors to reduce reliance on feedstocks that could be used in aviation and shipping.

4. **Streamline policy co-ordination for efficient SAF implementation**
    - Create an inter-ministerial task force to streamline SAF policy making and implementation, ensuring that agriculture, transport, energy and other ministries work together efficiently on SAF initiatives.
    - Develop clear road maps for SAF integration within national decarbonisation and industrial strategies, built on consistent and harmonised policies across ministries.

- Integrate SAF into new or existing special economic zones with clear SAF-specific incentives (such as aviation hubs or bio-industry hubs), accelerating progress in permitting, licensing and infrastructure development.
- Create feedstock price stabilisation mechanisms to shield SAF producers from fluctuating feedstock prices and ensure cost-effective, reliable feedstock supplies.

(B) A CO-ORDINATED REGIONAL FRAMEWORK FOR SAF DEVELOPMENT

Southeast Asia will need to work and act together, with a co-ordinated regional framework like the ASEAN Sustainable Aviation Action Plan to maximise the region's collective potential. A harmonised approach can unlock the benefits of collaboration, reduce inefficiencies and ensure that countries with differing resources, development stages and financial capacities can work together to meet their SAF targets. This may cover cross-border collaboration on regional value chain and feedstock supplies, harmonised regulations, and co-ordinated financial mechanisms to support large-scale SAF deployments.

1. **Develop a regional framework to facilitate trade**

   - Utilise the ASEAN Sustainable Aviation Action Plan to share best practices on aviation decarbonisation, facilitate information exchange and collaborate on developing an ASEAN Sustainable Aviation Roadmap.
   - Harmonise sustainability requirements and align trade policies.
   - Consider a "book and claim" system that enables airlines and SAF producers to trade SAF credits, helping countries without domestic production meet SAF mandates and scale production gradually.

2. **Foster regional collaboration for SAF deployments**

   - Encourage cross-border investment in SAF infrastructure and production facilities, particularly in countries with high production potential but limited financial means.
   - Promote joint SAF value chains across borders, ensuring that resources, knowledge, technical expertise and infrastructure are shared efficiently, which can lower costs and enhance regional energy security.
   - Explore regional financing schemes, such as SAF-focused funds or green bonds, to reduce the financial burden of deploying large-scale SAF plants, allowing countries to pool resources and share risks.

3. **Tailor policy support to regional variations**

   - Encourage regional cost benchmarking and knowledge sharing among Southeast Asian countries to optimise SAF deployment based on local economic conditions and technological feasibility.
   - Ensure equitable SAF deployment and do not disproportionately impact lower-income travellers – especially in archipelagic countries – or deter tourism, which is a major sector in Southeast Asia.
   - Offer specific incentives and support mechanisms to accommodate the varying stages of SAF development across countries.

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