PTX AND SUSTAINABLE AVIATION:

A ROADMAP FOR ASIA-PACIFIC

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ABOUT THE PROJECT

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Learn more about the project here.

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THE PROJECT EXPERT GROUP

This study has been supported by a Project Expert Group, which guided its initiation, scoping, and conclusion. Members of the Project Expert Group include:

Airbus, Axens, GIZ Thailand (H2Uppp), National Energy Technology Center (ENTEC) Thailand, PtX Lab Lausitz, Sasol, Siemens Energy, Sunshine Hydro, Topsoe, Jet Zero Australia.

The recommendations in this report are based on an independent analysis by the RSB and do not reflect the views of the funders or individual Project Expert Group members.

EXECUTIVE SUMMARY

The Asia–Pacific (APAC) region stands at a critical inflexion point in the race to decarbonise aviation. With global pressure mounting and sustainability standards tightening, this roadmap outlines how Power-to-X (PtX) fuels — particularly Power-to-Liquids (PtL) and Power-and-Biomass-to-Liquids (PBtL) — could become a credible pillar of APAC's low-carbon aviation future.

It provides the first integrated assessment of policy, sustainability, and resource readiness across the region, identifying where opportunities align — and where coordinated action is urgently needed.

EXECUTIVE SUMMARY

A REGION OF HIGH POTENTIAL — BUT UNEVEN READINESS

The study finds that APAC's resource base for PtX fuels is broad but highly uneven. Several countries possess significant renewable-energy potential, industrial CO_2 sources, and biomass residues, yet others face clear geographic and infrastructure constraints. Across the region, gaps in policy coherence, stakeholder capacity, and investment frameworks continue to limit large-scale deployment.

Japan, South Korea, and Singapore lead on governance and technology; Australia and China hold the strongest industrial and energy foundations; while India and Southeast Asian economies offer feedstock potential but face water stress, land-use pressures, and policy fragmentation. This diversity creates both challenges and opportunities — pointing to the need for coordinated regional cooperation rather than isolated national strategies.

WHAT STOPS PTX FROM SCALING — AND HOW TO UNLOCK IT

The heart of this roadmap lies in section 6. It shows that PtX fuels will not scale through engineering progress alone, but require coherent policy, market design, and regional collaboration. Six interlinked structural challenges persist: fragmented and inconsistent policy frameworks; imbalanced stakeholder ecosystems with limited capacity outside major economies; underdeveloped infrastructure for CO_2, hydrogen, and blending; a shortage of financing and de-risking instruments; divergent sustainability governance and certification systems; and limited integration of future aviation demand into renewable-energy planning.

These barriers — more than technical feasibility — define the region's real readiness gap.

EMERGING STRENGTHS AND COMPLEMENTARY ROLES

***No single country in APAC can meet all enabling conditions alone*.** Australia, China, and Japan show overall good readiness, while India, Indonesia, Malaysia, Singapore, South Korea, and Thailand occupy moderate positions. Their strengths are complementary: resource-rich economies can provide scale; advanced markets can drive technology, finance, and certification; and emerging producers can develop sustainable feedstock supply chains.

Five early opportunity clusters reflect these synergies — including Australia's coastal hydrogen hubs, India's PBtL feedstock base, biomass corridors in Indonesia and Malaysia, and technology and trading hubs in Singapore, Japan, and South Korea.

STRATEGIC PRIORITIES & THE ROAD AHEAD

To translate potential into progress, five regional priorities emerge: strengthening sustainability governance and shared knowledge; aligning certification systems; developing infrastructure and trade corridors; fostering technology and knowledge transfer; and mobilising finance and risk-sharing mechanisms

THE DECADE THAT MATTERS

The coming decade will determine whether PtX fuels become a niche innovation or a cornerstone of aviation decarbonisation in APAC. With credible sustainability governance, harmonised certification, and coordinated regional investment, the region can transform its diversity into strength — building a trusted, interconnected PtX ecosystem that underpins APAC's contribution to global net-zero aviation.

OBJECTIVES AND GOALS OF THIS STUDY

The primary objective of this study is to provide a first-of-its-kind, high-level overview of Power-to-X (PtX) fuels in the Asia–Pacific (APAC) region, with a particular focus on Power-to-Liquids (PtL) and Power-and-Biomass-to-Liquids (PBtL) pathways.

The study maps current policy developments, identifies key stakeholders, and highlights critical sustainability considerations to inform policymakers and industry stakeholders about the opportunities and challenges of scaling these emerging fuels sustainably.

By introducing PtL and PBtL into regional decarbonisation debates—alongside bio-based sustainable aviation fuel (SAF) options that currently dominate the market—the study aims to raise awareness, build knowledge, and support strategic decision-making. A further objective is to underline the role of sustainability certification frameworks in ensuring credibility, market access, and alignment with international standards.

Ultimately, the study seeks to provide a strategic foundation for future, more detailed assessments, such as national policy briefs, financing models, or sector-specific analyses. It reflects the perspectives of a broad range of stakeholders and highlights priority areas for research, investment, and policy action in APAC. These objectives guide the structure and analytical focus of the following sections.

LIMITATIONS OF THE STUDY

This study is a strategic scoping exercise that takes a primarily sustainability-focused and qualitative approach. While it provides a high-level overview of policies, stakeholders, and sustainability considerations for PtX fuels in APAC, several important limitations should be noted:

- **Qualitative emphasis:** The analysis relies mainly on qualitative screening and order-of-magnitude estimates. The findings are indicative rather than project-specific.
- **Data availability and language:** Access to consistent, comparable datasets across APAC is limited, and several sources required translation (e.g. Japanese, Hindi). Private-sector information (e.g. project pipelines, offtakes, costs) is often confidential or inconsistently reported, which fragments the industry picture. As a result, the assessments rely on public, verifiable sources and should be read as indicative rather than exhaustive.
- **Regional diversity:** APAC is highly heterogeneous in terms of policy, resources, and governance. Regional-level conclusions may mask significant national variations.
- **Early stage of deployment:** PtL and PBtL remain pre-commercial, with no large-scale plants yet in operation. This creates uncertainty around costs, learning curves, and policy packages needed for roll-out.
- **Electricity system interactions:** The study quantifies PtX electricity demand relative to renewable supply (Section 4.4.1) and frames sustainability considerations (Section 3.1.1). However, a full system-level prioritisation of renewable electricity use across competing applications (e.g. grid decarbonisation versus PtX fuels) is not attempted here, nor is an assessment of the temporal correlation challenge (i.e. ensuring PtX facilities can operate with variable renewables without prohibitive storage costs or efficiency penalties).
- **Resource logistics and trade feasibility:** The study does not assess the physical and infrastructural feasibility of delivering key PtX resources across APAC. Factors such as CO_2 transport and storage networks, hydrogen transport and storage constraints, e-fuel distribution infrastructure, port capacity, and cross-border trade logistics are recognised qualitatively but not modelled quantitatively. Likewise, inter-sectoral resource competition (e.g. domestic use vs. exports) is addressed conceptually rather than quantitatively. These logistical and market aspects will strongly influence the real-world availability, cost, and scalability of PtX fuel deployment across the region.
- **Supply–demand and techno-economic modelling:** This roadmap does not include detailed quantitative modelling of PtX fuel supply, demand, or cost trajectories. Such modelling would require project-level techno-economic data and market assumptions beyond the present scope.

Together, these limitations point to areas where further, more detailed analysis could build on the findings of this study. Country-specific techno-economic assessments, deeper exploration of financing and bankability, and system-level studies on electricity integration and temporal correlation would all complement the high-level sustainability lens applied here.

CONTENTS

ABBREVIATIONS

AEL	Alkaline Electrolyser
APAC	Asia–Pacific
APEC	Asia–Pacific Economic Cooperation
ARENA	Australian Renewable Energy Agency
ASEAN	Association of Southeast Asian Nations
ASTM	American Society for Testing and Materials
ATAG	Air Transport Action Group
AtJ	Alcohol-to-Jet
BAT	Best Available Technology
BtL	Biomass-to-Liquids
CAAC	Civil Aviation Administration of China
CAAS	Civil Aviation Authority of Singapore
CBG	Compressed Biogas
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation and Storage
CFD	Contract for Difference
CFPC	Clean Fuel Production Credit (US, Section 45Z)
CO_2	Carbon Dioxide
CO_2-eq.	Carbon dioxide equivalent
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation (ICAO)
CRM	Critical Raw Material
CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australia)
DAC	Direct Air Capture
DCCEEW	Department of Climate Change, Energy, the Environment and Water (Australia)
DI	Deionised (water)
EFB	Empty Fruit Bunches (from palm oil residues)
EIA	Energy Information Administration (United States)
ENTEC	National Energy Technology Center (Thailand)
EOR	Enhanced Oil Recovery
ETS	Emissions Trading System
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	FAO Statistical Database
FID	Final Investment Decision
FPIC	Free, Prior and Informed Consent
FT	Fischer–Tropsch (synthesis)
GFW	Global Forest Watch
GHG	Greenhouse Gas
GHI	Global Hunger Index
GFT	Gasification + Fischer–Tropsch
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit (German development agency)
GX Strategy	Green Transformation Strategy (Japan)
HEFA	Hydroprocessed Esters and Fatty Acids
H_2	Hydrogen
ICAO	International Civil Aviation Organization
IEA	International Energy Agency
ILUC	Indirect Land-Use Change
IRA	Inflation Reduction Act (United States)
IRENA	International Renewable Energy Agency
ISCC	International Sustainability and Carbon Certification
JCM	Joint Crediting Mechanism (Japan)
LCA	Life-Cycle Assessment
LCHS	Low Carbon Hydrogen Standard (UK)
LCFS	Low Carbon Fuel Standard (California, US)
Mt	Million tonnes
MtJ	Methanol-to-Jet
MSW	Municipal Solid Waste
OECD	Organisation for Economic Co-operation and Development
PBtL	Power-and-Biomass-to-Liquids
PEM	Proton Exchange Membrane (electrolyser)
PLI	Production Linked Incentive (India)
PtL	Power-to-Liquids
PtX	Power-to-X
RED III	Renewable Energy Directive III (EU)
RSB	Roundtable on Sustainable Biomaterials
RTFO	Renewable Transport Fuel Obligation (UK)
RWGS	Reverse Water–Gas Shift reaction
SAF	Sustainable Aviation Fuel
SOEC	Solid Oxide Electrolyser Cell
SPK	Synthetic Paraffinic Kerosene
TRL	Technology Readiness Level
WRI	World Resources Institute

TABLES AND FIGURES

1 SETTING THE SCENE: PTX FUELS AND SUSTAINABLE AVIATION IN APAC

Global air traffic is projected to continue rising through mid-century, with the *Asia–Pacific (APAC) region expected to be the leading driver of this growth* and to contribute more than half of the net gain in global passenger numbers by the early 2040s[1,2]. This expansion poses a particular challenge for aviation decarbonisation — the reduction of lifecycle greenhouse-gas (GHG) emissions linked to air travel — and, more fundamentally, for *defossilisation*: the shift away from fossil-based carbon towards renewable or circular carbon sources in the production of aviation fuels. Aviation is among the most difficult sectors to decarbonise because it depends on highly energy-dense fuels, operates over long distances, and involves aircraft with multi-decade service lives. The sector's historic reliance on inexpensive fossil kerosene compounds these challenges.

1.1. THE NEED FOR PTX FUELS IN SUSTAINABLE AVIATION

Sustainable Aviation Fuel (SAF) is widely recognised as the primary lever for reducing GHG emissions from long-haul and regional flights, where full electrification or hydrogen aircraft are unlikely to play a major role for decades. Forecasts for future SAF demand vary widely depending on policy ambition, technological progress, and resource availability. Industry and policy scenarios[2–4] indicate that SAF could eventually meet between roughly one-third and nearly all global jet-fuel demand by 2050 — equivalent to about 330–445 million tonnes annually — delivering more than half of the CO_2 reductions required for aviation's net-zero pathway. By contrast, more conservative market-based outlooks foresee production in the tens to low hundreds of million tonnes by mid-century. Together, these studies highlight both SAF's central role in aviation decarbonisation and the substantial uncertainty surrounding its future scale.

At present, nearly all commercial SAF production comes from Hydroprocessed Esters and Fatty Acids (HEFA) pathways[4]. HEFA fuels are chemically identical to fossil jet fuel and can be blended up to 50 per cent under ASTM standards, which set the global technical specifications for aviation fuels. However, HEFA relies on lipid-based resources such as used cooking oil and tallow, whose global supply is limited and slow to expand. Most outlooks expect HEFA feedstock availability to plateau around 2030, well before anticipated SAF demand peaks4. While new lipid sources — for example, cover crops or non-food oils grown on marginal land — are under development, their potential contribution remains uncertain. Other approved bio-SAF pathways, such as Alcohol-to-Jet (AtJ) and Biomass-to-Liquids (BtL), remain at early stages of deployment but are expected to grow in the coming decade.

Power-to-X (PtX) fuels provide an additional and complementary pathway. When produced using renewable electricity and sustainably sourced carbon, PtX fuels can achieve GHG-emission reductions above 90 per cent compared with fossil jet fuel5. This high mitigation potential makes them especially valuable once bio-based feedstocks reach their sustainable limits. Unlike biomass-only routes, PtX pathways depend mainly on renewable electricity and recycled or captured carbon, reducing pressure on land and water resources.

After 2030, SAF demand in APAC is expected to accelerate, requiring a rapid diversification of production routes beyond HEFA. Technologies such as Alcohol- and Ethanol-to-Jet (ATJ and ETJ) and Fischer–Tropsch (FT) conversion will be important in meeting this demand. Advanced pathways such as PtX fuels — including Power-to-Liquids (PtL) and hybrid Power- and-Biomass-to-Liquids (PBtL) routes — will be essential to achieving long-term net-zero goals. Within these projected transitions, PtX-based fuels are expected to become increasingly significant after 2035, as HEFA approaches feedstock limits and biomass availability levels off[5,6]. Ambitious global scenarios suggest that PtL fuels could supply up to around 40 per cent of total SAF by 2050[2]. If the APAC region were to capture a similar share, regional production could range from roughly 25 million tonnes per year in conservative market-based projections4 to about 55 million tonnes under the most ambitious Waypoint 2050 scenario[2]. These figures should be viewed as illustrative upper and lower bounds rather than forecasts, as achieving even the higher end would depend on unprecedented expansion of renewable-energy capacity and competition with other energy-system needs. Even at more moderate levels, however, PtX fuel deployment would represent a critical contribution to aviation's net-zero trajectory.

1.2. PTX: FROM RENEWABLE POWER TO SUSTAINABLE AVIATION FUELS

Having outlined the growing need for PtX fuels in sustainable aviation, it is important to understand the underlying processes that enable their production. PtX refers to a family of technologies that convert renewable electricity into a range of energy carriers and products. In this study, PtX pathways are understood as those in which hydrogen produced from renewable electricity through electrolysis — often referred to as *renewable or green hydrogen* — plays a central role, either as the main energy source or as a key yield-enhancing input alongside biomass.

Using *renewable electricity*[a] from sources such as wind, solar, hydro, or geothermal, PtX enables the production of hydrogen, synthetic fuels, and other industrial products without relying on fossil carbon. The "X" in PtX denotes the variety of possible outputs, including gases such as hydrogen or methane, liquids such as synthetic fuels or methanol, and even base chemicals used in fertilisers and plastics. PtX technologies are particularly relevant for sectors that cannot be fully electrified, such as aviation, shipping, or heavy industry, where they offer a route to deep defossilisation and long-term emission reduction[5].

At the core of PtX is *electrolysis*[b] — the process of splitting water into hydrogen and oxygen using renewable electricity. The resulting renewable hydrogen is a versatile energy carrier and the key building block for Power-to-X fuels. Its availability and cost will strongly influence how quickly PtX can scale in aviation[5].

Hydrogen production forms the starting point for many PtX processes: once produced, hydrogen can be combined with captured carbon to make the liquid fuels required for aviation. As illustrated in **Figure 1**, this chain links renewable electricity, water and raw materials[c] through hydrogen production to the creation of SAF and other low-carbon products.

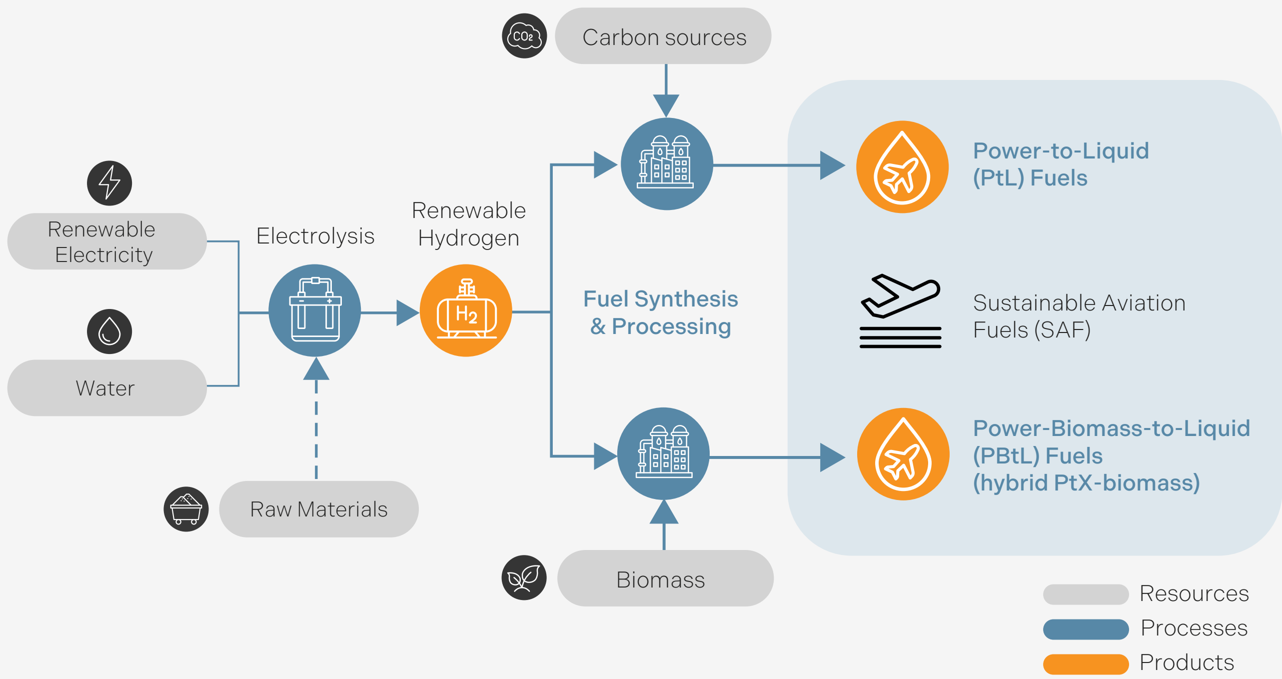


FIGURE 1 SIMPLIFIED OVERVIEW OF POWER-TO-X PATHWAYS AND STUDY SCOPE

The figure shows how renewable electricity and water are used to produce renewable hydrogen through electrolysis — a key intermediate for creating SAF and other products in different sectors. This study focuses on two types of SAF: Power-to-Liquids (PtL), produced from renewable hydrogen and captured carbon, and Power-and-Biomass-to-Liquids (PBtL), produced by adding renewable hydrogen to biomass-derived gases.

a. For simplicity, "renewable electricity" here refers to electricity that meets sustainability and additionality criteria as defined under frameworks such as the EU RED and RSB Global (see Section 5). Frameworks like CORSIA do not use this term explicitly but apply equivalent criteria to determine eligible low-carbon electricity.

b. Two main electrolyser technologies are commercially available today: alkaline electrolysis (AEL), which is the most established at industrial scale, and proton exchange membrane (PEM) electrolysis, valued for its flexibility and ability to work with variable renewable power. Solid oxide electrolysis (SOEC) is also emerging and could offer higher efficiency in the future as large-scale manufacturing becomes available.

c. In this study, "raw materials" refer to critical and structural materials that enable PtX fuel systems — including metals and catalysts used in the manufacture of electrolysers, fuel-synthesis units, and renewable-electricity infrastructure (see Sections 3.2.6, 4.1 and 4.2.3).

Two main technology families fall within the scope of this study: Power-to-Liquids (PtL) and Power-and-Biomass-to-Liquids (PBtL) (see **Figure 1**).

PtL pathways use renewable hydrogen produced by electrolysis together with captured carbon — for example from industrial, biogenic, or atmospheric sources — to make liquid fuels that can replace conventional jet fuel. The process is almost entirely driven by renewable electricity and therefore depends strongly on electricity supply and CO_2 capture. When powered by renewable sources, PtL can achieve very high greenhouse-gas reductions[2].

PBtL pathways, sometimes described as a hybrid PtX-biomass route, convert sustainable biomass or waste — such as forestry residues, agricultural by-products, or the biogenic fraction of municipal solid waste (MSW) — into gas through gasification. Renewable hydrogen from electrolysis is then added to this gas stream to improve carbon use and fuel yield. This approach makes PBtL more flexible than purely biomass-based routes: increasing the share of hydrogen boosts efficiency but also raises electricity demand[4].

A comparative overview of these two technology families is presented in **Table 1**, which summarises their main energy and carbon sources, indicative resource needs, costs, and current certification status.

TABLE 1 HIGH-LEVEL COMPARISON OF POWER-TO-LIQUIDS (PTL) AND POWER-AND-BIOMASS-TO-LIQUIDS (PBTL) PATHWAYS

CATEGORY	PTL – POWER-TO-LIQUIDS	PBTL – POWER-AND-BIOMASS-TO-LIQUIDS USES
Short Description	Produces liquid fuels from renewable hydrogen and captured CO_2 using using electrolysis.	Produces liquid fuels by gasifying sustainable biomass or waste and adding renewable hydrogen to increase carbon efficiency and fuel yield.
Energy Source	Renewable electricity (for hydrogen production and process energy).	Biomass for process energy, with additional renewable electricity for hydrogen production.
Carbon source	Captured CO_2 (industrial, biogenic, or from the air via direct-air capture(DAC)).	Biogenic carbon from residues, energy crops, or the biogenic fraction of waste.
Technical maturity	Demonstrated at pilot-to-early-demo scale; several projects under development.	Conceptually proven but gasification not yet commercial; pilot-scale demonstrations only.
Indicative costs (USD/t)	3,800–6,400 (Post-2040: 3,000–4,500)	5,400–8,600 (Post-2040: 3,100–4,800)
Maturity challenges and outlook	Technically advanced but electricity-intensive; requires large-scale electrolyser deployment and low-cost CO_2 capture.	Large-scale biomass and waste gasification remains challenging due to feed handling, contaminant removal, and syngas-cleaning needs; overall less mature than PtL despite conceptual advantages.

Example pathways and technology readiness

PtL fuels remain more expensive than PBtL at present (USD 5 400–8 600 vs. USD 3 800–6 400 per tonne[4]), mainly due to higher electricity use and CO_2-capture costs. By comparison, fossil jet fuel has averaged around USD 600–900 per tonne in recent years[7]. Both families are expected to become more cost-competitive after 2040 as renewable-power costs decline. Mechanisms such as book-and-claim systems can also help bridge the cost gap by stimulating early demand and supporting project bankability.

Within each family, *several process routes are being developed*, reflecting different feedstocks, conversion methods, and levels of maturity. These include Alcohol-to-Jet (AtJ), Methanol-to-Jet (MtJ), Gasification + Fischer–Tropsch (GFT), and Fischer–Tropsch (FT) synthesis pathways. All produce Synthetic Paraffinic Kerosene (SPK) — a renewable form of kerosene chemically similar to conventional jet fuel, which can be blended directly into existing aviation fuel without any engine modifications.

The use of such fuels in commercial aviation is governed by the ASTM D7566 standard issued by ASTM International, which sets out the technical specifications and blending limits for synthetic aviation fuels. Certification under ASTM D7566 is essential before any new pathway can be used in regular flight operations.

Table 2 summarises key examples of these PtL and PBtL pathways, showing their main process steps, current ASTM D7566 certification status, and indicative Technology Readiness Levels (TRLs). While some, such as PBtL-GFT and PtL-FT, have achieved ASTM approval, others remain at pilot or demonstration stage. In general, PtL technologies are more advanced, whereas PBtL routes still face technical hurdles in large-scale gasification and syngas upgrading[6].

TABLE 2 EXAMPLE PTL AND PBTL FUEL-PRODUCTION PATHWAYS, CERTIFICATION STATUS, AND INDICATIVE TECHNOLOGY READINESS LEVELS (TRLS)

PATHWAY	MAIN FEEDSTOCKS AND PROCESS	ASTM D7566 CERTIFICATION STATUS	IINDICATIVE TRL (2024)
PBtL-AtJ	Converts biomass or waste into alcohols (ethanol/isobutanol) and upgrades them into jet fuel.	Approved – Annex A4 (isobutanol) and A5 (ethanol)	6–7 (Pilot / early demo)
PBtL-MtJ	Converts biomass or waste into methanol, then upgrades to jet fuel.	Not yet approved	5–6 (Demo stage)
PBtL-GFT	Gasifies biomass or waste into synthesis gas, then converts it to jet fuel via Fischer–Tropsch.	Approved - Annex A1	6–7 (Pilot / early demo)
PtL-FT	Uses renewable hydrogen and captured CO_2 to produce jet fuel through Fischer–Tropsch synthesis.	Approved – Annex A1	6–7 (pilot to demo)
PtL-MtJ	Uses renewable hydrogen and captured CO_2 to make methanol, then upgrades it to jet fuel.	Not yet approved	5–6 (Lab to pilot)

Broader system and market benefits

PtX systems offer key advantages for aviation. Because many inputs and facilities can be shared across sectors, investments in PtX capacity for aviation fuels can also support markets such as shipping, renewable methane, and low-carbon chemicals[8]. This cross-sector use strengthens early business cases through shared supply chains and economies of scale. PtX production is also flexible: output can be adjusted in response to market or policy signals, and electricity or carbon sources can vary by region and technology.

The European Union (EU) is among the first regions to set binding blending targets for SAF and PtX-based fuels through its ReFuelEU Aviation initiative[9]. Early assessments of this policy framework indicate that integrated production systems serving multiple markets can lower overall costs and accelerate deployment. Although developed in a European context, these insights are relevant for the APAC region, where expanding PtX capacity could also support wider decarbonisation across hard-to-abate sectors and enhance energy resilience.

Although not a main focus of this study, *Biomass-to-Liquids (BtL)* pathways remain among the more established thermochemical routes to low-carbon fuels. Yet commercial-scale deployment remains challenging due to feed handling, syngas-cleaning requirements, and high capital costs. Over time, BtL systems could evolve into PBtL configurations as renewable-hydrogen costs fall, serving as a transitional step toward hybrid PtX–biomass routes.

1.3. PTX FUELS IN THE ASIA–PACIFIC: CONTEXT AND STUDY STRUCTURE

SAF progress and challenges in the APAC region

In the APAC region, achieving net-zero aviation will depend heavily on accelerating the use of *SAF*. The region is projected to account for the largest share of global passenger growth over the coming decades[1], meaning its choices on SAF development will strongly influence whether international climate goals for aviation can be met.

As outlined earlier, global SAF production is dominated by lipid-based HEFA fuels; this pattern is mirrored across APAC. Most current supply comes from HEFA pathways, which represent around 95 % of global output due to lower costs and early commercial maturity. Yet HEFA relies on finite lipid feedstocks such as used cooking oil and tallow, expected to reach their limits within this decade[4].

By contrast, PtX pathways, particular PtL, offer a longer-term, fully synthetic route but remain at early stages worldwide. Only a few pilot or demonstration projects exist in APAC, and none yet operate at commercial scale. Even under optimistic scenarios, producing PtL fuels still costs several times more than bio-based alternatives, and large-scale deployment will depend on abundant low-carbon electricity and reliable CO_2 supply.

Regional barriers and the need for sustainability

These barriers are compounded by regional energy and market conditions. Electricity demand in many APAC economies continues to rise rapidly, while coal remains a dominant source of generation. Without a major acceleration of renewables, there is limited near-term potential for surplus clean power to support PtX fuel production. Policy support and financing frameworks are also less developed than in the European Union or United States, and the region depends heavily on imported equipment such as electrolysers, catalysts, and carbon-capture systems.

At the same time, these challenges underline why *sustainability* is not only a safeguard but a necessity. Without robust standards and credible *certification*, PtX deployment could divert scarce renewable resources from other decarbonisation priorities or fall short of the greenhouse-gas reductions claimed. Ensuring strong sustainability governance will therefore be critical if PtX fuels are to play a constructive role in APAC's transition.

Purpose and structure of this study

Against this backdrop, this study provides a high-level overview of what PtX fuels could mean for APAC. It examines current policies and market conditions, assesses sustainability and resource implications, and outlines how certification frameworks can support credible deployment. The analysis concludes with recommendations for policymakers and industry, while identifying priority areas for further work—such as financing, country-specific policy instruments, and supply-chain readiness.

Figure 2 provides a visual overview of the study structure, showing how the analysis builds from policy and sustainability through resources and certification to the final roadmap and recommendations.

FIGURE 2 OVERVIEW OF THE STUDY STRUCTURE BY SECTION

2 PTX FUELS IN APAC: POLICIES AND STAKEHOLDERS

The APAC region is actively developing policy frameworks for SAF, with most existing measures currently focused on bio-based pathways. While explicit provisions for PtL and PBtL fuels are still emerging, several governments are introducing mandates, incentives, and strategic plans tailored to their national contexts. The region shows significant diversity in policy design and implementation, with leading economies advancing both regulatory and market-based initiatives. In contrast to regions such as the European Union, the United Kingdom, and the United States—where support mechanisms cover the entire SAF value chain[1,2,3]—policy activity in APAC is, at this stage, more concentrated on downstream measures such as blending targets and airline deployment, with upstream and midstream instruments gradually gaining attention.

2.1. SAF POLICY LANDSCAPE IN APAC

HEFA-based SAF remains the dominant pathway in APAC and provides a critical reference point for comparing the relative readiness of PtL and PBtL routes. In contrast, support for advanced PtX fuel pathways is still at pilot or early strategic-vision stage, with limited SAF-specific incentives in place.

These emerging frameworks are also shaped by deeper historical trajectories. APAC countries differ widely in how their energy systems evolved over the past century: Japan and South Korea emphasised import security and nuclear power, Australia developed as a fossil-fuel exporter, China built its industrial rise on coal while now rapidly scaling domestic renewables, and Singapore positioned itself as a refining and trade hub given its limited natural resources. Such legacies continue to influence both the scope and the pace of PtX-related policy development.

SAF Policy Landscape Overview

To illustrate the diversity of approaches, **Figure 3** maps and ranks current SAF-related policy instruments across the APAC region, grouped into direct policies, indirect support measures, and strategies and roadmaps. Within APAC, Japan, South Korea, and Singapore show a higher relative concentration of instruments, while most other countries remain in early stages of policy development.

Across the region, policy activity remains uneven, with most countries still in the early stages of defining their approach to SAF. Only a few have adopted binding mandates, while others focus on financial incentives or long-term planning frameworks.

DIRECT POLICIES

— such as blending mandates and legally binding targets — remain rare, with confirmed implementation in only a small number of economies. These instruments provide the clearest demand signal but require strong regulatory coordination and reliable supply chains.

INDIRECT MEASURES

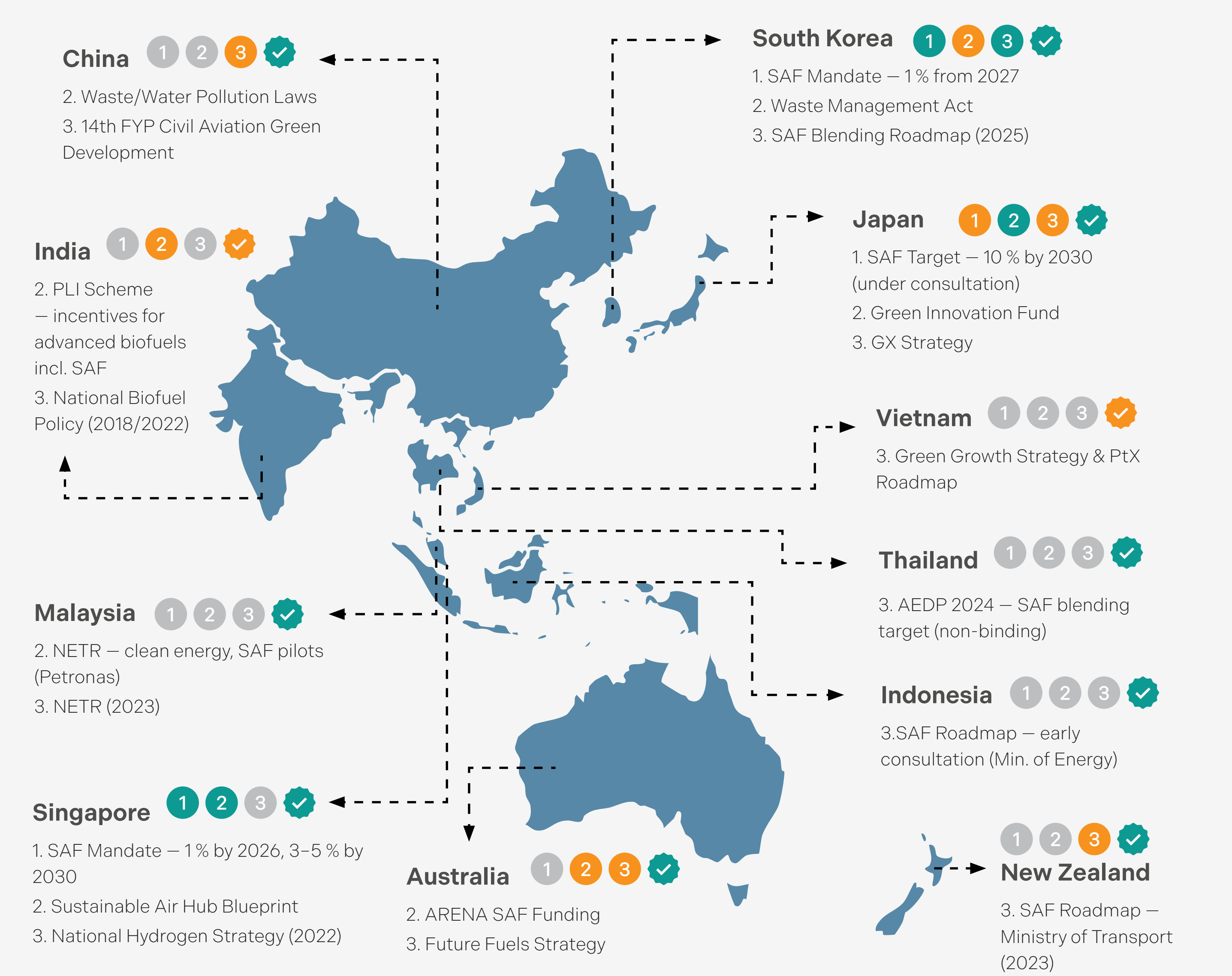
— including grants, tax incentives, or hydrogen programmes — are more widespread but fragmented. They help lower investment risk and stimulate early projects, yet they typically sit within broader renewable-energy or industrial strategies rather than aviation-specific frameworks.

STRATEGIC FRAMEWORKS

— including national SAF or PtX roadmaps — are becoming more common and signal growing political intent. However, they often lack binding mechanisms or dedicated funding, limiting their near-term impact.

Taken together, these patterns show that while regional ambition is increasing, most APAC countries remain at a formative stage compared with more mature policy environments in Europe and North America.

Annex I provides a detailed overview of country-level examples for each policy type, including blending mandates, incentive schemes, and regional national strategies.



POLICY INSTRUMENTS

1. **Direct policies:** Binding measures such as SAF blending mandates or legislated requirements that directly create demand.
2. **Indirect support measures:** Financial or regulatory incentives (e.g. subsidies, tax credits, R&D funds) that reduce costs or support feedstock and infrastructure.
3. **Strategies and roadmaps:** Non-binding plans that signal government intent, set targets, or guide long-term investment.

POLICY CONCENTRATION RANKING

- **High:** At least one enacted or legislated mandate, major funding programme, or published national strategy with specific SAF targets.
- **Moderate**: Active policy development, consultations, or financial incentives (e.g. subsidies, pilot funding) but no binding requirements yet.
- **Low**: Early-stage discussions, voluntary goals, or only indirect references to SAF in broader energy or climate strategies.

CORSIA PARTICIPATION

Status of countries in joining ICAO's global Carbon Offsetting and Reduction Scheme for International Aviation, which recognises SAF as a compliance option.

- Participating already (voluntary phase)
- Expected to join from 2027 (mandatory phase)
- Uncertain to join (e.g. China has not clarified participation despite ICAO listing it for 2027)

FIGURE 3 SAF POLICY LANDSCAPE MAP FOR THE APAC REGION

SAF-related policy instruments are grouped into three categories: (1) direct policies such as blending mandates, (2) indirect support measures including financial or fiscal incentives, and (3) national strategies and roadmaps. Country colours indicate the relative strength of policy activity within the region, while icons show each country's participation status in ICAO CORSIA. Example measures are displayed for selected countries under each policy type. Further details are provided in Annex I, which lists national instruments and programmes by category.

GLOBAL POLICY LEARNINGS FOR SAF AND PTX FUELS

Experience from the European Union, the United Kingdom, and the United States shows that no single policy instrument can drive large-scale deployment of SAF or PtX routes such as PtL and PBtL. Effective scale-up requires a package of complementary measures that combine demand-creation with price and investment support.

In Europe, the *ReFuelEU Aviation Regulation*[10] and associated *Innovation Fund*[11] have established blending mandates and funding windows for advanced fuels, but limited sub-targets and financing gaps still slow investment. In the US, the *Inflation Reduction Act (IRA)*[12] and *Clean Fuels Production Credit (Section 45Z)*[13] have sharply reduced the theoretical cost gap for synthetic fuels, yet deployment remains constrained by project-design and certification uncertainties. These global experiences underline that progress depends on coupling clear demand signals with stable price support and enabling conditions such as renewable electricity, hydrogen, and carbon-capture availability.

Across both policy literature and practice, five broad levers emerge as consistent success factors:

- *Mandates* that include advanced-fuel sub-targets, preventing crowd-out from mature routes such as HEFA[14–17];
- Price support or ***fiscal incentives*** that bridge the cost gap and improve project bankability;
- *Capital de-risking tools* such as contracts for difference or guaranteed offtake[18,19];
- ***System enablers*** that expand renewable-electricity and hydrogen supply[18]; and
- ***Feedstock mobilisation strategies*** that unlock sustainable biomass and waste for PBtL[17].

While these levers are increasingly visible in global frontrunners, few are yet observed in APAC, where most frameworks still focus on early bio-based pathways or general clean-energy goals.

Assessing policy readiness in APAC

To evaluate how prepared APAC countries are to scale PtL and PBtL fuels, this study identifies five policy building blocks that can be compared across national contexts:

1. ***SAF mandate status*** – the strength of direct policy signals;
2. ***Hydrogen-strategy maturity*** – an indicator of enabling-fuel infrastructure;
3. ***Clean-energy rollout*** – progress on renewable-power expansion;
4. ***Carbon-pricing mechanisms*** – instruments that support cost competitiveness; and
5. ***Biomass-mobilisation strategies*** – measures that ensure sustainable feedstock supply.

Each dimension is ranked as *high (green)*, *moderate (orange)*, or *low (grey)* based on current policy evidence. Dedicated PtL/PBtL sub-mandates, investment de-risking, and price guarantees are not yet observed anywhere in the region.

Table 3 summarises country-level maturity across these five dimensions, providing an early indication of which policy environments are relatively better positioned to enable PtL and PBtL scale-up over time.

TABLE 3 POLICY READINESS FOR PTL AND PBTL FUELS ACROSS THE APAC REGION

The table ranks five key policy dimensions by colour: green = high, orange = moderate, grey = low. Dedicated PtL/PBtL sub-mandates, price guarantees, and investment de-risking measures are not yet observed in the region.

COUNTRY	DEDICATED PTL/PBTL MEASURES	SAF MANDATE STATUS	HYDROGEN STRATEGY MATURITY	CLEAN ENERGY ROLLOUT	CARBON PRICING MECHANISM	BIOMASS MOBILISATION STRATEGY
Australia	Not established	No SAF mandate	H_2 Headstart + national strategy	Renewable Energy Zones (REZ)	No carbon pricing	Waste-wood PBtL pilots; new low-carbon fuel incentive (2024)
China	Not established	No SAF mandate	National H_2 plan in 14th FYP	Large-scale RE buildout	National ETS (partial coverage)	Limited biomass measures
India	No established	No SAF mandate	Draft national H_2 roadmap (under consultation)	Ambitious RE expansion targets	No ETS or carbon tax	Limited mobilisation measures
Indonesia, Thailand, Malaysia	No established	No SAF mandate	Early H_2 roadmaps	RE and biofuel expansion plans	No ETS or carbon tax	Residue/waste biomass policies (varies by country)
Japan	Not established	Blending law under renegotiation	Green Growth H_2 roadmap	Offshore wind & solar targets	No ETS or carbon tax	No mobilisation strategy
Singapore	Not established	SAF mandate enacted (2026 start)	National H_2 strategy (2022)	Solar + import capacity targets	No ETS or carbon tax	No mobilisation strategy
South Korea	Not established	SAF mandates legislated	National H_2 roadmap (announced)	Strong RE expansion targets	National ETS in force	Indirect bio-waste measures

Policy Ranking Conclusion

The combined mapping and ranking reveal three broad clusters across the APAC region. **Leaders** such as *South Korea* and *Singapore* have introduced SAF blending mandates and enabling frameworks, though none yet include dedicated incentives for *PtL* or *PBtL* fuels. **Mid-range countries** including *Japan, China*, and *India* are advancing rapidly on hydrogen and clean-energy strategies but still lack binding SAF demand or systematic biomass mobilisation. **Early-stage countries** in *Southeast Asia and Oceania* (for example *Indonesia, Thailand, Malaysia, Vietnam, New Zealand*, and *Australia*) remain focused on feasibility studies and early biofuel programmes. Australia's new production incentive for low-carbon fuels marks a modest step toward deployment incentives, but overall early-stage measures remain fragmented.

Across the region, enabling frameworks—particularly hydrogen strategies, renewable-energy expansion, and in some cases carbon pricing—are progressing faster than SAF-specific mandates. These efforts lay valuable groundwork for PtL and PBtL, yet the absence of explicit sub-targets, tailored fiscal incentives, and coordinated biomass strategies still limits investor confidence and risks confining progress to generic clean-energy deployment rather than aviation-specific outcomes.

Globally, the *European Union* remains ahead through binding SAF mandates, while the *United States* leads on financial incentives such as the *Inflation Reduction Act (IRA)* and state-level *Low Carbon Fuel Standards* but lacks a federal mandate. Both regions are expanding hydrogen and renewable-energy frameworks and experimenting with carbon pricing, yet PtL and PBtL remain secondary priorities within broader energy strategies. For APAC, the findings point to three main gaps:

1. **Limited SAF demand signals**,
2. **Generic and early-stage regulatory frameworks**, and
3. **Absence of structural de-risking instruments** such as grid infrastructure, credit schemes, and long-term offtake agreements.

Closing these gaps will be essential if the region is to convert its clean-energy momentum into meaningful progress on aviation decarbonisation.

2.2. STAKEHOLDERS AND INITIATIVES MAPPING

The deployment of SAF including PtX fuel pathways, across the APAC region depends not only on national policy frameworks but also on a diverse network of public and private actors shaping early market development. Mapping these actors helps identify the main drivers of progress, the emerging trends influencing investment and technology, and the coordination gaps that still need to be addressed.

This analysis draws on a structured stakeholder-mapping exercise covering eleven APAC countries. The assessment focuses primarily on PtX-related pathways but, where data are limited, also includes broader SAF activity. Countries were selected to reflect a mix of leading and emerging markets. Publicly available information was reviewed to identify active stakeholders and initiatives, which were then qualitatively assessed as having a **high**, **moderate**, or **low** level of presence and visibility across each category (see **Table 4**).

Emerging Initiatives and Collaboration Platforms

Alongside national policies and stakeholder engagement, a growing number of *initiatives and partnerships* are driving early progress toward PtX and synthetic fuel development across the APAC region. These range from corporate alliances and bilateral government agreements to research pilots and investment partnerships. While most activity remains at the *proof-of-concept or demonstration* stage, these initiatives play a crucial role in connecting policy ambition with on-the-ground action.

The analysis focused on PtX and synthetic-fuel pathways, particularly *PtL*, while also recognising broader SAF initiatives that influence PtX deployment. Eleven initiative types were identified, grouped by their primary role in enabling technology, market demand, or system integration (see **Table 5**).

TABLE 4 STAKEHOLDER LANDSCAPE ACROSS APAC

Stakeholder landscape across APAC, illustrating qualitative presence levels of eight actor groups shaping SAF and PtX fuel markets, based on structured country-level screening.

The table ranks the presence of each stakeholder group in APAC by colour: green = high, orange = moderate, grey = low.

	COUNTRY										
STAKEHOLDER GROUP	AUSTRALIA	CHINA	INDIA	INDONESIA	JAPAN	MALAYSIA	NEW ZEALAND	SINGAPORE	SOUTH KOREA	THAILAND	VIETNAM
Fuel Producers & Developers	High	Moderate	Moderate	Moderate	High	Moderate	Moderate	Moderate	High	High	Moderate
Governments & Policy Agencies	Low	High	Moderate	Moderate	Moderate	High	Moderate	Moderate	Moderate	High	Moderate
Technology Providers	High	Moderate	Moderate	Moderate	High	Low	Moderate	Moderate	Moderate	High	Low
Airlines & Off-takers	Low	Moderate	Low	Low	Moderate	Low	Low	Low	Moderate	Low	Low
Finance & Investors	Moderate	Low	Low	Low	Moderate	Low	Low	Moderate	Low	Low	Moderate
Research & Academia	Moderate	Low	Low	Low	Low	Low	Low	Low	Low	Moderate	Low
Alliances & Consortia	Moderate	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
Infrastructure & Utilities	Low	Low	Low	Low	Low	Low	Low	Low	Moderate	Low	Low

Types of initiatives observed in APAC

- **Corporate customer alliances** – Coalitions of non-aviation companies committing to SAF purchases, helping to create early market demand. Examples include the *Clean Skies for Tomorrow* coalition and Japanese corporate participation in *All Nippon Airways (ANA)'s SAF Flight Initiative*.

- **Technology development projects** – Research and pilot activities focused on PtL, *Alcohol-to-Jet (AtJ)*, and *Hydroprocessed Esters and Fatty Acids (HEFA)* fuels, such as *CSIRO's PtL pilot in Australia* and *NEDO-led AtJ demonstrations in Japan*.

- **Industrial alliances and manufacturer partnerships** – Cross-sector collaborations and engagement by original equipment manufacturers (OEMs) to advance certification and supply-chain readiness, e.g. *ACT FOR SKY, Airbus–Singapore Airlines*, and *Boeing–ANA*.

- **Feedstock development initiatives** – Efforts to secure sustainable feedstock supply, led by *Australia* (e.g. *Carinata trials, Project Swift*) and smaller programmes in *China* and *Malaysia*.

- **Policy development programmes** – Frameworks that formalise SAF uptake, including *Singapore's 1 % SAF mandate by 2026*, *Japan's national SAF roadmap, India's draft SAF Policy* (1–5 % by 2030), and *Thailand's Alternative Energy Development Plan* (AEDP) target of 1–8 % by 2036.

- **Infrastructure and logistics pilots** – Early projects integrating SAF into airport fuel supply systems, such as *Neste–Changi Airport* in Singapore and Melbourne Airport's blending trials.

- **Fuel producer–airline partnerships** – Offtake and co-investment agreements that underpin commercial demand, for example *Qantas–Airbus* and *Japan Airlines–IHI*.

- **Bilateral collaboration and market mechanisms** – Government-level memoranda of understanding (MoUs) and emerging carbon frameworks, including the *Australia–Singapore MoU*, the *Japan–US Clean Energy Partnership*, and SAF linkages under *Singapore's carbon tax* and *Australia's Safeguard Mechanism*.

- **Financial institution–technology partnerships** – Capital mobilisation initiatives such as the *Asian Development Bank* (ADB) and *Japan Bank for International Cooperation (JBIC)* programmes that support SAF and PtX project financing.

Across the region, SAF-related initiatives are expanding quickly but remain **fragmented** and **project-based**. Most activity focuses on HEFA and *AtJ pathways*, while *PtL* and *Power-and-Biomass-to-Liquids (PBtL)* initiatives are still at pilot or planning stages. Cross-sector collaboration is increasing — particularly between airlines, technology developers, and governments — but coordination across value-chain segments (e.g. feedstock, finance, and logistics) remains limited.

Overall, the emerging picture suggests that **APAC's SAF and PtX markets are entering a coordination phase**: many actors are engaged, but few are yet connected through structured frameworks or long-term offtake agreements. Strengthening these linkages will be critical to move from isolated pilots to integrated regional value chains.

TABLE 5 INITIATIVE MAPPING ACROSS APAC COUNTRIES

Stakeholder landscape across APAC, illustrating qualitative presence levels of eight actor groups shaping SAF and PtX fuel markets, based on structured country-level screening.

The table ranks the presence of each initiative category by colour: green = high, orange = moderate, grey = low.

INITIATIVE CATEGORY	COUNTRY										
	AUSTRALIA	CHINA	INDIA	INDONESIA	JAPAN	MALAYSIA	NEW ZEALAND	SINGAPORE	SOUTH KOREA	THAILAND	VIETNAM
Corporate Customer Alliance	green	green	green	green	green	grey	green	green	green	green	green
Technology Development	green	green	green	green	orange	grey	green	green	grey	green	green
Industrial Alliance	orange	orange	orange	orange	orange	orange	orange	orange	green	orange	orange
Aircraft Manufacturer Partnerships	green	green	orange	orange	green	grey	orange	orange	grey	orange	orange
Feedstock Development	green	orange	orange	orange	orange	orange	orange	orange	grey	orange	orange
Policy Development	grey	grey	orange	orange	grey	green	grey	orange	orange	orange	orange
Infrastructure & Logistics	orange	grey	orange	orange	grey	grey	orange	orange	grey	orange	orange
Fuel Producer–Airline/Cargo	orange	orange	grey	grey	orange	orange	orange	grey	orange	grey	grey
Bilateral Collaboration	orange	orange	orange	grey	orange	grey	orange	grey	grey	grey	grey
Carbon Market Development	grey	orange	grey	grey	orange	grey	grey	grey	grey	grey	grey
Financial Institution–Technology	orange	grey	grey	grey	grey	grey	orange	grey	grey	grey	grey

Examples of Emerging PtX fuel Initiatives in APAC

While most SAF activity in APAC remains HEFA-based, a growing number of stakeholders are advancing PtL and PBtL pathways. The cases below illustrate tangible progress across feasibility, pilot, and early demonstration stages (non-exhaustive):

- **China (Ordos, Inner Mongolia)**[20,21]: The State Power Investment Corporation (SPIC), in partnership with Cathay Pacific and others, is developing multiple PtL plants combining wind-powered hydrogen production with captured CO_2 for e-SAF synthesis. Additional joint projects involving Sinopec and TotalEnergies include SAF plants with medium-term PtX integration potential.
- **India (Panipat and emerging partnerships)**[22,23]: Indian Oil Corporation (IOC) and DLanzaJet are constructing an Alcohol-to-Jet (AtJ) facility at Panipat, slated for operation by 2026 and designed for later PtX integration. Boeing and Hindustan Petroleum Corporation Limited (HPCL) are exploring synthetic SAF production under national decarbonisation frameworks.

- **Japan (PBtL and synthetic-fuel pilots)**[24]: NEDO-backed consortia led by Mitsubishi Power, JERA, and Toyo have demonstrated continuous biomass-to-jet operation via gasification + FT; ENEOS and other industrial partners have completed small-scale synthetic-fuel demo plants.
- **Japan (airline–industry collaboration)**[25]: JAL, Airbus, and Nippon Paper are developing a domestic wood-based SAF supply chain with PBtL potential under evaluation, supported by corporate and government R&D funding.
- **Australia (Whyalla, South Australia)**[24]: Zero Petroleum's "Plant Zero.SA" aims to produce **synthetic e-fuels** using renewable hydrogen and captured CO_2, with state government support and partnerships across the aviation value chain.
- **New Zealand**[24]: A government–industry consortium is advancing the country's first PtL demonstration facility leveraging abundant renewable electricity and Fischer-Tropsch synthesis for e-SAF production.
- **Singapore (Jurong/Bukom cluster)**[26]: Aether Fuels, backed by Temasek/Xora, is developing proprietary CO_2- and waste-carbon-to-liquids technology for e-SAF, integrated with Singapore's refining and port infrastructure.

These examples underline that while PtX production in APAC is still nascent, pilot- and pre-commercial-scale capacity is emerging across several markets, translating policy ambition into tangible industrial projects and laying the groundwork for regional trade and scale-up opportunities.

3 SUSTAINABILITY AND RISK CONTEXT FOR PTX FUELS IN APAC

The sustainability of PtX fuels depends both on the wider environmental and social context in which projects are developed and on how key resources are sourced and managed. As PtX pathways begin to scale in the APAC region, understanding these dimensions becomes essential for ensuring that synthetic fuels deliver real climate benefits without creating unintended burdens on ecosystems, communities, or competing sectors. Sustainability considerations extend beyond GHG performance alone: they encompass the availability and responsible use of renewable electricity, water, carbon, biomass, land, and critical raw materials, as well as the governance frameworks that safeguard local livelihoods and social well-being. This section provides an integrated overview of these risks and considerations, outlining the enabling conditions that must be in place to support credible, equitable, and environmentally sound PtX fuel deployment across APAC.

This section combines two complementary layers:

- **Section 3.1 – Country-level sustainability risks:** A high-level screening across eight APAC countries highlighting cross-cutting, fuel-independent pressures such as deforestation risk, water stress, and social governance that shape the enabling environment.
- **Sections 3.2-3.3 – Resource-specific sustainability considerations:** A closer look at the key inputs to PtX fuels, including electricity, water, carbon, biomass, land, and critical raw materials. The analysis reflects current best practices and insights from recent studies on how these resources can be sourced and managed sustainably in the APAC context.

Together, the country screen provides the backdrop, and the resource lens provides the project-facing sustainability considerations.

This section applies a sustainability perspective only; certification requirements and sourcing rules defined under international frameworks such as CORSIA, the EU Renewable Energy Directive (RED III), and the RSB Standard for Advanced Fuels are addressed separately in Section 5. The analyses here also form the basis for the quantification of resource demand and availability in Section 4 and are revisited in the synthesis and recommendations in Section 6.

3.1. COUNTRY-SPECIFIC SUSTAINABILITY RISKS

The first layer of this assessment is a high-level, fuel-type independent screening of environmental and social risks across eight APAC countries. It draws on the RSB Risk Assessment Tool[27] and Screening Tool[28], which use internationally recognised data sources and provide robust and comparable indicators of systemic pressures, such as deforestation, water stress, and social governance, that shape the enabling environment for PtX deployment in the region.

The methodology applied a multi-indicator risk scoring approach across five sustainability dimensions:

1	**Deforestation** – assessed using average tree cover loss due to permanent agriculture-driven deforestation (2022–2024; Global Forest Watch[29]).
2	**Water stress** – based on current levels and 2050 projections under a business-as-usual scenario (Aqueduct Water Risk Atlas[30]).
3	**Human and labour rights –** assessed using national governance and human rights indices[31].
4	**Rural and social development** – aligned with UN Human Development Index metrics[32].
5	**Food security** – assessed through the Global Hunger Index[33].

Each country received a composite score between 5 (very low risk) and 15 (very high risk), derived from five sustainability dimensions scored on a 1–3 scale (1 = low risk, 3 = high risk). Final scores were grouped into five categories: very low, low, medium, high, and very high risk. Detailed indicator definitions, data sources, and scoring thresholds are provided in Annex II.

Key results include (see Table 6):

- India scores highest overall (high risk), driven by combined pressures on deforestation, water stress, labour rights, and food security.
- China and Thailand fall into the medium risk category, with water stress and deforestation as notable concerns.
- Australia and Malaysia show low risk overall but face region-specific challenges (e.g. deforestation in Malaysia, water stress in parts of Australia).
- Japan, Singapore, and South Korea are classified as very low risk, reflecting stronger governance and lower pressures on deforestation and food security.
- No country was classified as very high risk.

TABLE 6 **COUNTRY-LEVEL SUSTAINABILITY RISK SCREENING RESULTS**

Country-level sustainability risk screening results for eight selected APAC countries, based on five sustainability dimensions (deforestation, water stress, human and labour rights, rural and social development, and food security).

The table classifies risks by colour: dark green = very low, green = low, yellow = moderate, orange = high, dark orange = very high.

COUNTRY	INDICATOR: DEFORESTATION	WATER STRESS	HUMAN AND LABOUR RIGHTS	RURAL AND SOCIAL DEVELOPMENT	FOOD SECURITY	TOTAL SCORE (RISK)
Australia	dark orange	yellow	dark green	dark green	dark green	green
China	dark orange	yellow	yellow	dark green	dark green	yellow
India	dark orange	dark orange	yellow	yellow	yellow	orange
Japan	yellow	dark green	dark green	dark green	dark green	dark green
Malaysia	dark orange	dark green	dark green	dark green	dark green	green
Singapore	yellow	dark green	dark green	dark green	dark green	dark green
South Korea	dark green	yellow	dark green	dark green	dark green	dark green
Thailand	dark orange	dark orange	dark green	dark green	dark green	yellow

Key cross-cutting observations and implications for PtX fuels:

- **Deforestation**[29]: Permanent agriculture-driven deforestation is the most critical land-use pressure in the APAC region. Between 2022 and 2024, agriculture accounted for 98.5 % of forest loss in Thailand, 95 % in Malaysia, and 92 % in India, underscoring intense conversion pressures. Australia (58 %) and China (48 %) also show considerable pressures, while Japan, Singapore, and South Korea remain below 17 %. For PtX, the relevance of these risks depends strongly on biomass sourcing. PBtL pathways can minimise deforestation impacts by focusing on residues, plantation thinnings, and low-ILUC energy crops, which are highlighted in Section 3.2.4. PtL pathways face indirect risks where renewable energy expansion is poorly sited and encroaches on forested areas (e.g. bioenergy projects or large-scale solar/wind).

- **Water stress**[30]: Water stress is a defining sustainability challenge in parts of APAC, with India and Thailand experiencing severe scarcity, medium stress in Australia, China, and South Korea, and lower levels in Japan, Malaysia, and Singapore. In a PtX context, risks are most acute for electrolysis-based hydrogen production if it relies on freshwater or groundwater. These risks can be mitigated by minimising the use of freshwater, substituting seawater, and applying sustainable desalination and wastewater handling practices as outlined in Section 3.2.2.

- **Human and labour rights**[31]: Human and labour rights risks vary across APAC, with higher concerns in India and China, and generally stronger protections in Japan, Singapore, South Korea, Malaysia, and Australia. For PtX, this highlights the need to apply international safeguards — such as RSB's Principles & Criteria or resource-specific frameworks like the OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas[34] — to ensure consistent protection regardless of local enforcement capacity (see Section 3.3).

- **Rural and social development**[32]: Rural and social development conditions shape how communities experience large-scale energy projects. Countries with lower human development indicators, such as India, are more exposed to risks of displacement or inequality if projects are not designed inclusively. In higher-HDI countries such as Japan, South Korea, and Singapore, stronger institutions may help manage these risks. Across all contexts, PtX deployment can enhance outcomes when projects incorporate benefit-sharing and community co-benefits, guided by international frameworks (see Section 3.3).

- **Food security**[33]: Food security risks are highest in India, moderate in Thailand, and low in the other assessed countries. In a PtX context, PBtL risks arise mainly where feedstock sourcing competes with food or feed crops. These risks can be minimised by prioritising agricultural residues, plantation biomass, and low-ILUC energy crops, as highlighted in Section 3.2.4. Certification schemes such as RSB and RED III reinforce this by restricting eligibility to wastes and residues, helping to safeguard against food–fuel competition.

In summary, sustainability risks vary widely across APAC. India emerges as the highest-risk country overall, while Japan, Singapore, and South Korea show very low systemic risks. Deforestation and water stress stand out as the most critical cross-cutting challenges, particularly where agriculture and land conversion pressures are intense. At the same time, many risks can be mitigated if PtX deployment focuses on sustainable feedstocks, minimises freshwater dependence, and applies robust social safeguards through international frameworks.

Building on this high-level country screening, the following sections move from a broad, fuel-independent perspective to a more specific assessment of PtX fuel sustainability. Sections 3.2–3.7 examine key resource inputs, including electricity, water, carbon, biomass, land, and raw materials, highlighting how they can be sourced and managed responsibly in APAC. Section 3.3 complements this with a deeper look at social sustainability dimensions, highlighting how PtX projects can strengthen community outcomes if designed inclusively.

3.2. ENVIRONMENTAL SUSTAINABILITY CONSIDERATIONS FOR PTX FUELS

Following the country-level sustainability risk assessment in Section 3.1, this section examines the sustainability considerations of specific resources required for PtX fuel production. The analysis is guided by the RSB Principles & Criteria[35], a robust and widely recognised framework developed through a multi-stakeholder process to set holistic environmental and social standards for responsible fuel production. **Figure 4** summarises the 12 principles, their focus, and how they relate to the resource dimensions examined in Sections 3.2 and 3.3.

Using this reference, the subsections describe sustainability aspects resource by resource, covering electricity, water, carbon, biomass, land, and critical raw materials, and integrate insights from recent studies and best practices on how these inputs can be sourced and managed responsibly in the APAC context. References to other frameworks, such as CORSIA are included where they help illustrate sustainability challenges, while certification requirements themselves are addressed separately in section 5.

RSB PRINCIPLE	DESCRIPTION	RELEVANCE FOR PTX FUEL PRODUCTION
1. Legality	Ensures operations comply with national and international laws, including environmental, land, and water regulations.	Critical for safeguarding land rights, water access, and waste handling in PtX projects (3.2.2, 3.2.5, 3.2.7).
2. Planning, Monitoring & Improvement	Requires transparent impact assessments, stakeholder engagement, and continuous sustainability monitoring.	Enables robust governance across all PtX resource dimensions; foundational for ESMPs and risk screening.
3. GHG Emissions	Mandates significant lifecycle GHG reductions compared to fossil fuels.	Central to evaluating electricity sourcing, CO_2 feedstocks, and biomass conversion in PtL and PBtL pathways (3.2.1, 3.2.3, 3.2.4).
4. Human & Labour Rights	Protects workers' rights, safety, and fair conditions across the supply chain.	Relevant for raw material extraction (e.g. cobalt, nickel), biomass collection, and infrastructure development (3.2.4, 3.2.6).
5. Rural & Social Development	Promotes local economic development, capacity building, and equitable benefit-sharing.	Important for biomass feedstock systems and land-intensive renewable energy projects (3.2.4, 3.2.5).
6. Local Food Security	Safeguards food access and prevents negative impacts on food systems.	Ensures residue use in PBtL does not undermine local food or fodder systems (3.2.4, 3.2.5).
7. Conservation	Protects biodiversity, ecosystems, and conservation values.	Prevents PtX infrastructure and biomass sourcing from impacting sensitive ecosystems (3.2.4, 3.2.5).
8. Soil	Maintains or enhances soil health, structure, and nutrient balance.	Ensures sustainable residue removal and land use in PBtL pathways (3.2.4).
9. Water	Protects water quality and quantity, and respects water rights.	Critical for electrolysis, desalination, and wastewater reuse in PtL systems (3.2.2).
10. Air Quality	Minimizes air pollution from operations and supply chains.	Relevant for biomass gasification and combustion emissions in PBtL (3.2.4, 3.2.7).
11. Inputs & Waste Management	Promotes safe use of chemicals, circularity, and responsible waste handling.	Applies to raw material sourcing, desalination brine, and catalyst disposal (3.2.6, 3.2.7).
12. Land Rights	Requires respect for formal and customary land tenure, including FPIC.	Essential for siting renewable energy and biomass projects in APAC (3.2.5).

FIGURE 4 RSB PRINCIPLES AND THEIR RELEVANCE TO SAFEGUARD SUSTAINABLE PTX FUEL PRODUCTION.

3.2.1. Electricity

Electricity is the cornerstone of PtL pathways and the most critical input for PtX fuel production. Its significance lies not only in the absolute quantities required, dominated by hydrogen electrolysis, but also in the sustainability of its sourcing. Renewable electricity is widely recognised as the long-term benchmark, avoiding direct GHG emissions and reducing reliance on fossil fuels. However, certification frameworks diverge in their treatment of eligible electricity inputs: while RED III and RSB apply strict renewable-only criteria, other schemes such as CORSIA and the EU's emerging Low-Carbon Hydrogen Delegated Act adopt a broader view of low-carbon options. This evolving policy landscape underscores the importance of clear safeguards to ensure credibility and consistency in PtX deployment.

SUSTAINABILITY DIMENSIONS LINKED TO ELECTRICITY SUPPLY:

- **Eligibility of electricity inputs**: Certification schemes such as RED III and the RSB Advanced Fuels Standard require fuels to be produced from renewable electricity sources, applying safeguards on additionality, temporal correlation, and geographic matching. CORSIA applies broadly similar principles but, unlike RED III or RSB, does not prescribe exclusive reliance on renewables. Instead, it recognises a broader set of low-carbon options if they meet lifecycle GHG reduction requirements and are accompanied by sustainability declarations. Biomass electricity occupies a special case: while classified as renewable under RED III, it is excluded for RFNBO production. RSB accepts biomass electricity if it meets broader safeguards, and CORSIA recognises it conditionally if certified under ICAO-approved schemes. Hydropower is recognised as renewable under RED III, RSB, and CORSIA, subject to standard safeguards. While generally eligible, large-scale projects may raise site-specific sustainability risks (e.g. biodiversity impacts, resettlement), which require careful due diligence.

- **Low-carbon transitional options**: In several APAC countries, nuclear power already plays a role in electricity generation. Under CORSIA, low-carbon electricity sources beyond renewables may be recognised if they demonstrate verifiable lifecycle GHG reductions and are certified under ICAO-approved schemes. The EU's Delegated Act for Low-Carbon Hydrogen (2025) sets a methodology for non-renewable hydrogen but currently excludes nuclear PPAs, with a review scheduled by 2028. Such options are generally viewed as transitional, while wind and solar remain the long-term benchmark for PtX fuels.

- **Resource efficiency and land use**: Renewable electricity is not impact-free. Solar PV and wind power require substantial land areas and large volumes of critical raw materials such as silicon, copper, silver, rare earths, and steel. Extraction and processing of these resources often occur in regions with weak governance, posing environmental and social risks (see Section 3.1.6). For hydropower, resource impacts are less about materials and more about ecological and social trade-offs, including river ecosystem disruption and potential methane emissions from reservoirs.

- **No-go areas and safeguards**: According to the RSB Principles and Criteria (see **Figure 4**, Principles 7 and 12) and CORSIA, renewable electricity projects must not be developed in areas of high biodiversity value or where food security is at risk. Projects must also respect land rights, ensure fair labour practices, and involve stakeholder consultation, especially important in APAC countries with contested land tenure.

- **Finite resource perspective**: Experts increasingly stress that renewable electricity should be considered a finite and competing resource. In APAC, no clear prioritisation exists between aviation, shipping, steelmaking, or grid decarbonisation. This underlines the need for sustainability frameworks that ensure electricity is directed to applications with the greatest climate benefit.

In summary, renewable electricity is the cornerstone of PtX fuel production, but its sustainability depends on strict sourcing criteria, responsible land and material use, and robust safeguards. While transitional low-carbon sources may play a limited role in some APAC contexts, wind and solar remain the long-term benchmark, and prioritisation across competing uses will be essential.

3.2.2. Water

Water is a critical input to PtX fuel production, primarily for hydrogen generation via electrolysis. Proton Exchange Membrane (PEM) and Alkaline (AEL) electrolysers typically require around 9 litres of deionised water per kilogram of hydrogen produced[36,37]. Solid Oxide Electrolysis (SOEC) systems—now nearing commercial deployment, use steam rather than liquid water and have similar or slightly lower overall water requirements, depending on system design and recovery efficiency. Even though these are small amounts compared to other sectors such as agriculture or municipal supply, safeguarding this input is essential, as freshwater is a finite and socially critical resource.

Existing regulatory frameworks, including EU RED III, the RSB Standard for Advanced Fuels, and ICAO CORSIA, already establish clear safeguards: groundwater and drinking water should not be used, and withdrawals in regions of high water stress must be avoided. In line with RSB's Water Impact Assessment Guidelines[38], projects must carry out risk assessments at catchment level, considering local availability, competing uses, and ecological flows.

SUSTAINABILITY DIMENSIONS LINKED TO WATER SUPPLY INCLUDE:

- **Freshwater safeguards**[35,39]: RED III, RSB, and CORSIA all prohibit the use of drinking water and require avoidance of withdrawals in high-stress areas. According to RSB's Principles (see **Figure 4**, Principle 9), water rights and ecosystem needs must be respected, and impacts assessed through robust management plans.
- **Seawater desalination**: In water-stressed APAC regions, seawater desalination is increasingly viewed as the most viable large-scale option. Sustainability depends less on technical feasibility, which is well proven, and more on siting, energy sourcing, and waste management[40,41]. RSB requires desalination plants to be powered by renewable electricity and to apply safe brine disposal or valorisation measures[39]. Research further suggests minimum distances (≥4 km) from Marine Protected Areas to reduce sensitive ecosystem impacts. Co-benefits, such as supplying excess desalinated water to communities, can support social acceptance.
- **Industrial wastewater reuse**: Recovering water from industrial or municipal wastewater streams is emerging as a complementary option[40]. This reduces pressure on freshwater resources and aligns with the RSB principle of cascading resource use. While still at pilot scale in APAC, wastewater reuse offers strong synergies for regions with established chemical and refining industries.
- **Emerging PtX-specific criteria**: Dedicated research projects[42] and PtX think tanks[43] are advancing additional safeguards tailored to large-scale seawater use. Proposed criteria include: exclusive reliance on renewable electricity for desalination; mandatory desalination in regions where the World Resource Institute (WRI) water stress index30 exceeds 40 %; safe brine management in compliance with ISO 14001, combined with efforts to valorise brine through mineral recovery and circular use[44,45]; minimum siting distances from Marine Protected Areas (≥4 km)[41,43]; and comprehensive water management plans with ecological and social impact assessments. Some initiatives also highlight potential co-benefits, for example supplying surplus desalinated water to local communities.

In summary, freshwater safeguards are already robust under existing certification schemes. The main sustainability frontier for APAC lies in scaling desalination and wastewater reuse responsibly, ensuring renewable energy integration, safe waste handling, and community co-benefits. Overall, water is not a universal limiting factor for PtX fuels, but a site-specific sustainability concern, with risks concentrated in water-stressed regions where competition for resources is already high.

3.2.3. Carbon Source

Carbon is an essential feedstock for producing PtX fuels, as it provides the basis for synthesising hydrocarbon molecules. The carbon source determines both the GHG performance and the long-term sustainability of PtX fuel pathways. International frameworks such as RED III and its Delegated Acts, CORSIA sustainability criteria, and voluntary certification systems such as the RSB Standard for Advanced Fuels, define which CO_2 sources are eligible for use.

Broadly, three categories of CO_2 are recognised:

- **Biogenic CO_2:** Released from processes such as anaerobic digestion, fermentation, or biomass combustion (e.g. biogenic fraction of incinerated municipal solid waste (MSW)).
- **Direct air capture (DAC):** Capturing CO_2 directly from ambient air, offering a theoretically unlimited source consistent with long-term climate neutrality.
- **Fossil CO_2:** Eligible if generated from unavoidable process emissions arising from industrial activities such as cement or lime production, or combustion of fuels for products other than waste gases (e.g. fossil fraction of incinerated municipal solid waste (MSW)).

SUSTAINABILITY DIMENSIONS LINKED TO CARBON SUPPLY INCLUDE:

- **GHG mitigation performance:** Sourcing carbon from biogenic waste, residue streams, and DAC generally provides substantial reductions compared to using fossil jet fuel. Process emissions may be accepted as transitional inputs but only until the underlying industries decarbonise. RED III, CORSIA, and RSB all require verifiable lifecycle reductions, with stricter safeguards under RED III and RSB.
- **Feedstock origin and land use:** Sustainability standards exclude the use of dedicated energy crops due to indirect land-use change (ILUC) risks. Eligible biogenic CO_2 is therefore restricted to wastes and residues (RSB; CORSIA; RED III).
- **Long-term availability:** DAC is the most future-proof option, but requires large amounts of renewable electricity (and potentially water) to operate sustainably. Biogenic CO_2 is limited by availability, while process emissions will decline over time as industries decarbonise.
- **Resource efficiency:** DAC is highly energy-intensive and must be carefully integrated with renewable energy systems. Biogenic CO_2 may face competing uses (e.g. bio-based chemicals, materials). Reliance on process emissions risks prolonging fossil-based industrial infrastructure if not strictly time-limited.
- **Framework approaches:** RED III and RSB prioritise residues and DAC while excluding fossil-derived CO_2 from avoidable processes. CORSIA applies a broader, more permissive approach: waste gases may be used if they are unavoidably generated during the production of another primary product, subject to ICAO methodological specifications[46].

Taken together, these criteria establish a sustainability hierarchy: biogenic CO_2 sources and DAC are prioritised; unavoidable fossil process emissions may serve as transitional sources; and other fossil-derived CO_2 from avoidable sources are excluded under all frameworks.

3.2.4. Biomass

Biomass is a flexible resource that can serve multiple roles in the PtX fuel system. It can contribute indirectly by providing renewable electricity and heat through combustion or gasification, and directly as a carbon-rich feedstock for Power-and-Biomass-to-Liquids (PBtL) fuel production. In PBtL (hybrid PtX–biomass) pathways, biomass residues are gasified to generate biogenic syngas, which is upgraded with electrolytic hydrogen to increase carbon utilisation and fuel yield. Two main PBtL configurations are considered: (i) co-feeding biogenic syngas and renewable hydrogen into Fischer–Tropsch synthesis; and (ii) gasification of biomass residues as the primary carbon source, supplemented with renewable hydrogen for syngas balancing and hydrogenation.

International frameworks such as RED III and its Delegated Acts, CORSIA sustainability criteria, and the RSB Standard generally restrict eligible biomass to wastes and residues, while constraining food and feed crops due to high risks of indirect land-use change (ILUC).

A recent study of sustainable feedstock sources in Southeast Asia[47], together with complementary references, identified seven biomass residues particularly relevant for the APAC region, as listed in **Table 7**. These feedstocks were selected based not only on their availability, but also on their alignment with key sustainability safeguards. Agricultural residues such as rice straw, bagasse, and corn stover offer high potential for fuel synthesis while supporting circular resource use and reducing open burning. Palm oil and forestry residues require strict traceability to avoid deforestation and biodiversity risks. Municipal solid waste and cassava residues present opportunities for waste valorisation, provided that competing uses and environmental safeguards are respected. These considerations are consistent with the ASEAN Strategy on Sustainable Biomass Energy (2020–

TABLE 7 **SELECT BIOMASS RESIDUES AND WASTES RELEVANT FOR PBTL PATHWAYS IN THE APAC REGION**

Select biomass residues and wastes relevant for PBtL pathways in the APAC region and related sustainability considerations (based on RSB Southeast Asia Feedstock Study[47] and complementary sources).

BIOMASS SOURCE	SUSTAINABILITY CONSIDERATIONS	REF.
Sugarcane bagasse	Widely used in cogeneration; over-extraction may reduce availability for local energy and materials.	47
Rice straw/residues	Excess removal risks soil nutrient depletion and erosion, while open burning practices are unsustainable. Utilising these residues for PBtLcould provide benefits if safeguards apply.	47
Wheat straw	Soil carbon and nutrient retention must be safeguarded; excessive removal risks soil degradation and erosion. Competing uses (bedding, soil cover) and collection logistics also need to be managed	47, 49
Palm oil residues, incl. Empty fruit bunches (EFB)	Linked to deforestation and biodiversity loss; it must be ensured that residues are truly waste streams and not driving expansion.	47, 50
Corn stover	Provides soil organic matter; excessive removal risks soil fertility decline and reduced water retention.	49,
Municipal solid waste (MSW)	The waste hierarchy must be respected; only the dry organic fraction of MSW is suitable; competition with recycling streams is a concern.	51, 52
Cassava processing residues	High availability as a by-product of starch processing, but improper handling can cause water pollution.	47
Forestry residues	Risk of deforestation leakage and biodiversity impacts; careful traceability required.	8, 53

2030)[48], which promotes residue-based systems as a low-emission alternative to traditional biomass and encourages inclusive, community-level energy solutions.

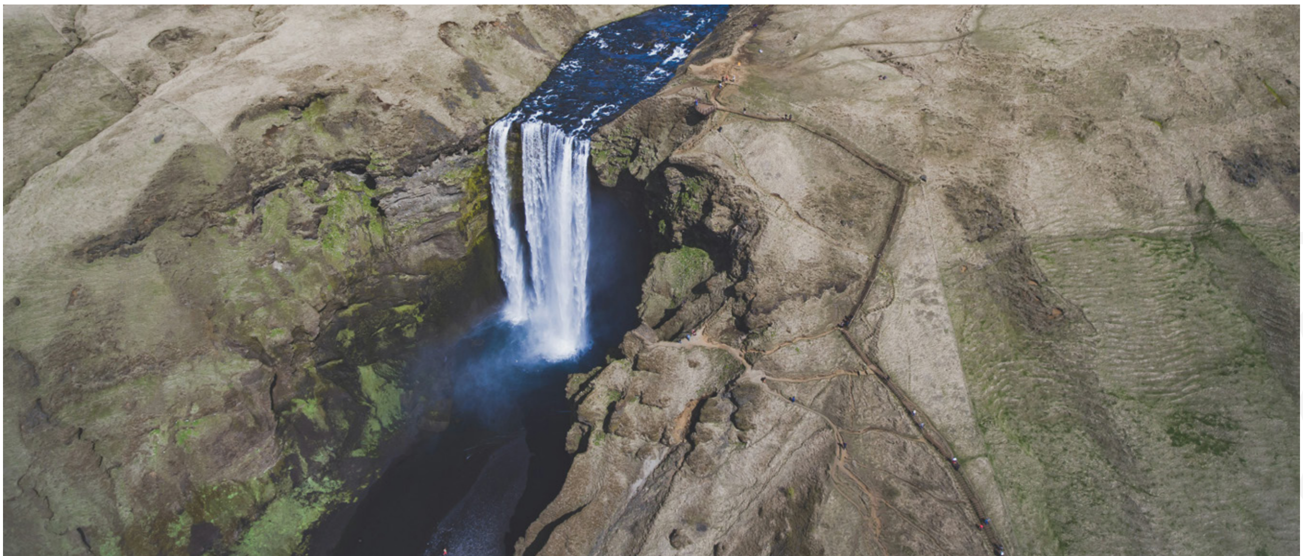
In addition to residues and wastes, certain dedicated energy crops may be considered if they qualify as low-ILUC-risk feedstocks under sustainability certification schemes. These include crops grown on degraded, marginal, or fallow land, or produced through yield increases that do not displace food or feed production. Such crops could provide substantial additional biomass potential in APAC, but require robust safeguards for biodiversity, soil health, and water use.

While **Table 7** summarises feedstock-specific risks and opportunities, there are several cross-cutting sustainability dimensions that apply across all categories.

CROSS-CUTTING SUSTAINABILITY DIMENSIONS

- **GHG performance**: Residues and wastes can deliver strong emission reductions, provided that collection, transport, and conversion processes minimise fossil energy inputs. Under the RSB/CORSIA GHG methodology, certain wastes and residues may even carry a baseline GHG value of zero.
- **Soil and nutrient management**: Excessive removal of agricultural residues (e.g. rice straw, corn stover) risks depleting soil organic carbon and impairing fertility and water retention. Certification schemes require residue retention thresholds to safeguard soil health.
- **Competing uses**: Many residues already support local energy, material, or livelihood systems (e.g. bagasse for cogeneration, forestry residues for pulp and board). PBtL projects must ensure that SAF production does not undermine these uses or create new trade-offs.
- **Waste hierarchy**: For MSW, sustainability requires strict adherence to the waste hierarchy — prioritising reduction, reuse, and recycling before energy recovery.
- **Deforestation and biodiversity risks**: Palm oil and forestry residues carry heightened risks of being linked to deforestation or biodiversity loss. Even secondary streams require strict traceability and safeguards against leakage effects.
- **Social safeguards**: Collection and handling of residues must respect land rights, protect food security, and ensure fair labour practices, consistent with RSB Principles on rural development and community rights (see **Figure 4**).

In summary, residues and wastes are the most viable biomass inputs for PBtL in APAC, but their sustainable mobilisation requires robust certification, careful traceability, and governance measures that balance GHG benefits with soil, biodiversity, and socio-economic safeguards.



3.2.5. Land Use

Land is a cross-cutting dimension for PtX fuel deployment, relevant both to biomass-based PBtL pathways and to the infrastructure footprint of renewable electricity systems. Its sustainable management is critical to ensuring that fuel production does not generate unintended environmental or social trade-offs.

International sustainability frameworks already provide clear safeguards. The EU RED III excludes feedstocks sourced from land with high biodiversity value or high carbon stock, such as primary forests, wetlands, or peatlands. The RSB Principles and Criteria establish "no-go" areas for land conversion, including High Conservation Value (HCV) zones, and require that indirect land-use change (ILUC) risks be carefully assessed. Similarly, CORSIA sustainability criteria apply comparable restrictions to ensure alignment with global climate and biodiversity objectives[54].

SUSTAINABILITY DIMENSIONS LINKED TO LAND USE INCLUDE:

- **Biomass feedstocks**: While residues and wastes do not directly require new land, unsustainable removal can indirectly affect soil fertility, carbon stocks, or local uses, potentially driving compensatory land conversion elsewhere. Certification frameworks therefore require residue-retention thresholds and ILUC safeguards[47,55].
- **Renewable electricity infrastructure:** Large-scale solar PV and wind farms demand significant land area, though far less than bioenergy crops. Conflicts may still arise in APAC over siting in agricultural zones or biodiversity-sensitive areas. Multi-use strategies such as agrivoltaics (dual use of land for agriculture and solar PV), siting on degraded land, or co-location with existing infrastructure are increasingly promoted to mitigate such conflicts[40,56].
- **No-go areas:** RED III, CORSIA, and RSB all prohibit project development in high-biodiversity or high-carbon-stock areas (e.g. primary forests, peatlands). RSB further requires participatory land-use planning and landscape-level conservation strategies.
- **Social safeguards**: Land rights, indigenous access, and community impacts represent a critical social dimension. RSB (see **Figure 4**, Principles 12 and 2) requires respect for formal and customary tenure rights and mandates free, prior, and informed consent (FPIC) for affected communities.

In summary, land-use considerations for PtX fuel pathways centre on protecting no-go areas, managing indirect effects from residue diversion, promoting multi-use approaches for renewable energy siting, and safeguarding community land rights.

3.2.6. Raw Materials

Critical Raw Materials (CRMs)[a] play a central role in PtX fuel production, both in renewable electricity infrastructure and within fuel synthesis processes. Solar PV and wind turbines depend on elements such as silicon, silver, indium, copper, and rare earths, alongside large volumes of steel, aluminium, and concrete. Electrolysers are especially material-intensive: Proton Exchange Membrane (PEM) systems rely on platinum and iridium, while Alkaline (AEL) and Solid Oxide Electrolysers (SOEC) depend more on nickel, cobalt, and zirconium[56]. Downstream synthesis routes (e.g. Fischer–Tropsch, methanol-to-jet, alcohol-to-jet) require additional catalysts based on cobalt, nickel, and copper.

Unlike electricity, water, or CO_2, the sustainability risks linked to CRMs arise primarily from mining, extraction, and global supply chains. These impacts are largely upstream and indirect from PtX projects themselves, yet they are significant given the reliance of solar PV, wind power, and electrolysers on materials such as rare earths, copper, cobalt, and nickel.

KEY SUSTAINABILITY DIMENSIONS FOR CRMS INCLUDE:

- **Supply risk and geopolitical concentration:** Many CRMs are sourced from a small number of countries. Over 70 % of global cobalt originates in the Democratic Republic of Congo, while platinum and iridium are concentrated in South Africa[43]. This raises risks of supply bottlenecks and price volatility for scaling PtX fuels in APAC.
- **Environmental impacts:** Mining and refining of cobalt, nickel, and rare earths are associated with high GHG emissions, land and water degradation, and local pollution. These impacts often occur in countries with weak environmental governance[56].
- **Social dimensions:** Extraction of several CRMs has been linked to labour rights violations, unsafe working conditions, and conflicts with local communities. The OECD Due Diligence Guidance for Responsible supply Chains of Minerals from Conflict-Affected and High-Risk Areas[34] provides a framework to address these risks (see Section 3.2).
- **Circularity and substitution:** Recycling of platinum group metals, nickel, and cobalt from spent electrolysers and catalysts can reduce pressure on primary supply. Research into substitution, such as reducing iridium loading in PEM systems, is also advancing[43].
- **Framework gaps and emerging criteria:** CRMs are not explicitly covered under RED III or CORSIA. However, PtX-specific sustainability approaches are emerging, including proposals for responsible sourcing standards, recycling targets, and greater supply chain transparency (e.g. PtX Lab Lausitz 2025[43]). The RSB Principles and Criteria (see **Figure 4**) also provide a foundation, particularly on ecosystems, social rights, and resource efficiency.

In summary, CRMs are indispensable enablers of PtX fuels but carry distinct sustainability and supply risks. Ensuring secure and responsible access in APAC will require applying global due diligence frameworks, promoting recycling and substitution, and developing PtX-specific sustainability criteria that complement existing certification schemes.

a. In this study, "critical" refers to materials that combine high economic importance with high supply risk in global clean-energy and PtX supply chains. The degree of criticality may vary by region; for example, cobalt is considered critical in the EU but less so in China due to domestic access and processing capacity.

3.2.7. Other Environmental Considerations

In addition to electricity, water, carbon sources, biomass, land use, and raw materials, several further environmental aspects are important for the sustainable deployment of PtX fuels in APAC. While less frequently quantified, these dimensions are embedded in international sustainability frameworks such as the RSB Principles and Criteria, EU RED III, and CORSIA, and are increasingly reflected in PtX-specific research[43].

KEY ADDITIONAL ENVIRONMENTAL DIMENSIONS INCLUDE:

- **Air emissions and local air quality**: Beyond lifecycle GHG performance, PtX fuel facilities may generate local pollutants such as nitrogen oxides (NO_x), sulphur oxides (SO_2), and particulate matter (PM), primarily from biomass gasification, combustion for process heat, or backup fossil energy use in PBtL and hybrid routes. Pure electrolysis-based PtL pathways typically have minimal direct air emissions, but siting and permitting still require compliance with national air-quality and emission standards. Air pollution remains a major environmental and public-health challenge across much of APAC, with several economies ranking among the world's most polluted urban regions. Consequently, many countries have adopted strict industrial emission limits—such as China's GB 13223-2011[57] for thermal processes, India's CPCB58 norms (2015/2021) for NO_x and PM, and Japan's Air Pollution Control Law[59] regulating SO_2 and NO_x. These are reinforced by national Environmental Impact Assessment (EIA) frameworks[60], which require monitoring and mitigation of local pollutants for all large-scale energy and industrial projects. In parallel, the RSB Principles and Criteria (see **Figure 4**, Principle 10) establish safeguards for air quality and require application of best available techniques to minimise local pollution. Together, these frameworks ensure that PtX fuel deployment contributes to decarbonisation without aggravating existing air-quality pressures, a key consideration in densely populated APAC regions.
- **Waste and by-products management**: PtX fuel production generates solid and liquid by-products, including brine from desalination, ash and slag from biomass gasification, and spent catalysts or membranes containing critical metals. International standards (RSB, ISO 14001[61]) and PtX think tanks[43] recommend a strict waste hierarchy approach: prioritising reduction, reuse and recycling, minimising hazardous waste, and ensuring safe disposal to avoid soil, air, or water contamination. International standards (RSB, ISO 14001[61]) and PtX think tanks[43] recommend a strict waste hierarchy approach: prioritising reduction and recycling, minimising hazardous waste, and ensuring safe disposal to avoid soil, air, or water contamination. Effective waste governance is essential to prevent burden-shifting from global GHG savings to local environmental harms (see **Figure 4**, Principle 11).
- **Ecosystems and biodiversity safeguards**: PtX fuel projects may interact with sensitive ecosystems, especially where biomass residues are collected near biodiversity hotspots or where infrastructure development affects coastal and forested areas. International standards establish clear "no-go" areas such as primary forests, wetlands, and legally protected sites (see **Figure 4**, Principle 7). RSB explicitly mandates biodiversity protection and maintenance of ecosystem services. This is highly relevant in APAC countries with globally significant ecosystems, including Indonesia, Malaysia, and the Philippines. Recent analyses, including PtX Lab Lausitz (2025)[43], further emphasise the importance of integrating biodiversity safeguards into PtX project planning to ensure alignment with climate and conservation goals.

In summary, additional environmental aspects — air emissions, waste governance, and biodiversity protection — must be integrated alongside core resource considerations. Applying strict safeguards ensures that PtX fuel deployment reduces global emissions without shifting environmental burdens to local ecosystems or communities.

3.3. SOCIAL SUSTAINABILITY CONSIDERATIONS

Alongside environmental aspects, the deployment of PtX fuels in APAC must integrate robust social safeguards. Production and distribution intersect with multiple social dimensions, from working conditions in global supply chains to local community impacts of land and biomass use. This section frames social risks and opportunities with reference to international best practices, particularly the RSB Principles and Criteria (see **Figure 4**), complemented by frameworks such as the OECD Due Diligence Guidance[34] for Responsible Supply Chains of Minerals and recent PtX-specific guidances[43] .Alongside environmental aspects, the deployment of PtX fuels in APAC must integrate robust social safeguards. Production and distribution intersect with multiple social dimensions, from working conditions in global supply chains to local community impacts of land and biomass use. This section outlines social risks and opportunities with reference to international best practices, particularly the RSB Principles & Criteria (see **Figure 4**), complemented by other key international frameworks and recent PtX-specific studies, such as the one developed by PtX Lab Lausitz[43].

KEY SOCIAL SUSTAINABILITY DIMENSIONS INCLUDE:

- **Human and labour rights (RSB Principle 4)**: Expansion of renewable electricity infrastructure, electrolyser manufacturing, and biomass supply chains requires strong safeguards to protect workers. This includes fair wages, safe and decent conditions, and the prevention of exploitative practices. While many risks lie upstream in global CRM mining (see Section 3.1.6), project-level measures in APAC will be critical to avoid replicating poor labour conditions.
- **Community engagement and land access (RSB Principles 12 & 2)**: Land-intensive activities such as biomass harvesting and renewable energy parks may affect local communities through restricted access to agricultural land, contested tenure rights, or displacement. Free, prior, and informed consent (FPIC) and ongoing stakeholder engagement are essential. Social impact assessments should be mandatory, participatory, and gender-sensitive to ensure that vulnerable groups are not excluded.
- **Raw material supply chains**: As highlighted in Section 3.2.6, the extraction of CRMs such as cobalt, nickel, and platinum-group metals is often linked to unsafe labour conditions, human rights violations, and inadequate consultation. While these risks are global, they directly affect PtX deployment in APAC through reliance on imported technologies. Due diligence frameworks (OECD) and emerging PtX-specific criteria are critical to ensuring responsible sourcing.
- **Biomass residues and local livelihoods (RSB Principles 5 & 6)**: Residues such as rice straw, bagasse, and forestry by-products can be sustainable feedstocks but often play key roles in local livelihood systems (fodder, cooking fuel, small-scale energy). Diverting them to PtX fuel production without safeguards may undermine food security or income streams. RSB requires explicit assessment of food security and local development impacts before mobilising residues, and projects should co-design solutions with affected communities.
- **Equity and benefit-sharing (RSB Principle 5)**: PtX projects must ensure that benefits are equitably distributed, including local employment, infrastructure, and capacity building. Avoiding "enclave" projects — where benefits accrue mainly to global offtakers while local communities bear environmental and social burdens — is critical for long-term acceptance. Large-scale PtX deployment may also risk driving up local electricity demand and prices; this underscores the need to link PtX projects with parallel investments in energy access and grid reinforcement. Explicit benefit-sharing mechanisms (e.g. community development funds, grid investments) can generate durable co-benefits aligned with the SDGs.
- **Capacity building and technology transfer (RSB Principle 5)**: Beyond risk management, PtX projects should actively contribute to long-term capacity building, including workforce training, SME development in supply chains, and knowledge transfer. Initiatives such as the RSB Academy provide practical models for training and awareness-raising.

In summary, the social sustainability of PtX fuels in APAC depends on safeguarding labour rights, ensuring equitable land access, managing raw material and biomass trade-offs, and embedding benefit-sharing. By aligning with international standards and co-designing projects with local communities, PtX deployment can strengthen social acceptance and contribute positively to inclusive development.

4 QUANTIFICATION OF RESOURCE DEMAND AND AVAILABILITY IN APAC

The large-scale deployment of PtX fuels in APAC depends not only on policy and sustainability safeguards, but also on the *availability, location, and allocation of key resources.* This section provides a quantitative overview of resource requirements and indicative availability for PtL and PBtL pathways. It translates sustainability principles into order-of-magnitude estimates to illustrate the scale of electricity, water, carbon feedstocks, biomass, and critical raw materials (CRMs) needed to produce synthetic fuels at meaningful volumes. It also considers how these resources may compete with other sectors and the potential role of regional trade and cross-border linkages in closing gaps.

- **Section 4.1** assesses how much of each resource is needed to produce 1 ton of SAF (PtL and PBtL) and what this could imply for PtL at scale by mid-century.
- **Section 4.2** maps the availability of those resources across APAC and consolidates findings in Section 4.2.4.
- **Section 4.3** examines resource competition and trading potentials of PtX fuel resources and outlines APAC trading roles and corridors for resources and enabling technologies.

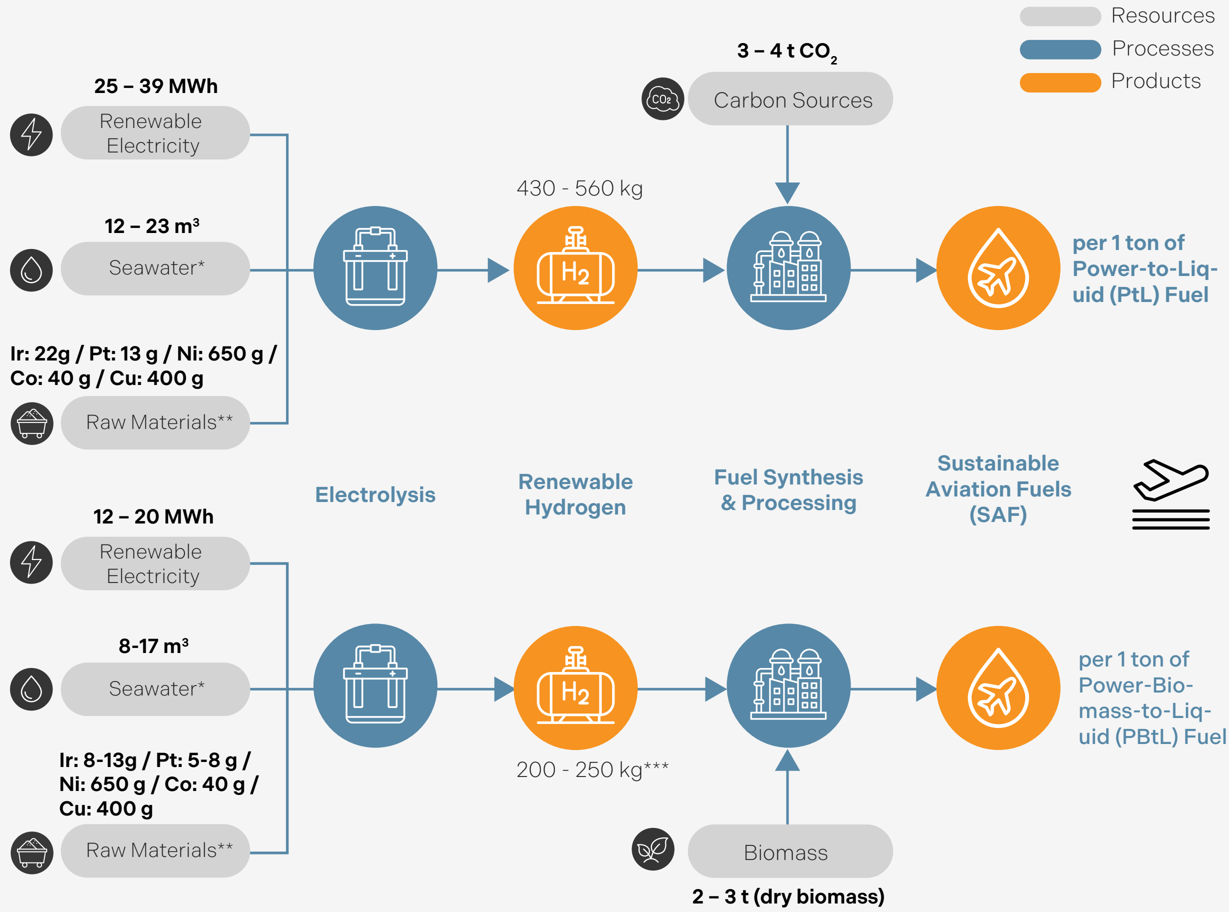
Results highlight regional diversity and sustainability implications rather than project-specific forecasts. Infrastructure and logistics (grid integration, CO_2 transport and storage, hydrogen distribution, cross-border trade) are recognised as critical but remain beyond scope; technology improvements, seasonal variability, land-use constraints, and evolving policy/market conditions will require system-level assessment to refine long-term outlooks.

4.1. PTX FUEL RESOURCE DEMANDS & APAC 2050 SCALE-UP

Pathway-Specific Resource Demand

Producing PtX fuels requires substantial inputs. Electricity, water, carbon or biomass feedstocks, and selected critical raw materials are needed in both PtL and PBtL pathways. Their overall sustainability depends not only on greenhouse-gas performance but also on how these inputs are sourced, managed, and scaled over time.

Figure 5 shows the indicative inputs per tonne of SAF produced via PtL or PBtL. Values are order-of-magnitude process inputs at the plant gate (LHV 43 MJ kg^{-1}) and cover electricity, water, CO_2 feedstock for PtL, biomass feedstocks for PBtL, and selected critical raw materials (Iridium (Ir), Platinum (Pt), Nickel (Ni), Cobalt (Co), Copper (Cu)). Hydrogen is shown for context as an on-site intermediate, produced from electricity and water via electrolysis. Actual requirements depend on process configuration, technology choice, and operating conditions; the ranges are intended to give a high-level sense of how resource demands may look for the two fuel pathways. Detailed assumptions, methods, and conversion factors are provided in Annex III.



* *Water values are seawater intake for desalination; DI water ≈ 6.0–11.5 m³ (PtL) and 4.0–8.7 m³ (PBtL) per t SAF.*

** *Raw materials assume PEM electrolysis; Ir/Pt scale with H_2 throughput (AEL would lower Ir/Pt ~to zero and increase Ni).*

*** *PBtL hydrogen assumption: 0.20–0.25 t H_2 per t fuel, typically enabling ~90 %+ carbon efficiency (configuration-dependent).*

FIGURE 5 **INDICATIVE RESOURCE DEMAND TO PRODUCE 1 TON OF SAF VIA PTL AND PBTL**

*Ranges show order-of-magnitude primary inputs per tonne of final fuel (LHV 43 MJ kg⁻¹): electricity, water, CO_2 feedstock (PtL only), and biomass (PBtL only). Hydrogen is an on-site intermediate produced from electricity and water via electrolysis (shown for process context, not additive). PBtL values reflect a conservative hydrogen-assisted setting***. See Annex III for methods, assumptions, and sources.*

Figure 5 underscores how the two pathways lean on different inputs in practice. PtL is driven by access to renewable electricity and sustainable CO_2, so project viability hinges on power availability, grid connection, and credible CO_2 sourcing and accounting. PBtL turns first on the mobilisation of sustainable residues and wastes; adding renewable hydrogen to the syngas raises carbon use and fuel yield, but also lifts electricity needs, so designs must balance efficiency gains against local power costs and constraints.

Water volumes are moderate overall, yet siting matters—desalination or limited reuse can become binding in arid or water-stressed regions. Critical raw materials are small in mass but strategic: the iridium and platinum values shown reflect a PEM electrolyser baseline and scale with the amount of hydrogen produced; choosing alkaline electrolysis would lower iridium and platinum requirements and raise nickel, while SOEC shifts needs toward ceramic and specialty components.

Resource Implications of Scaling PtL Fuels in APAC to 2050

This section stress-tests the *resource implications of large-scale* PtL in the APAC region by 2050. Using the per-tonne input coefficients from **Figure 6**, we translate illustrative PtL production volumes into *order-of-magnitude requirements* for electricity, hydrogen, CO_2, water and renewable generation capacity. The aim is not to forecast, but to indicate the scale of inputs under plausible ranges and to highlight where constraints are most likely to emerge. PBtL is not included in this stress test, because current market projections rarely quantify hybrid PtX–biomass routes.

In both cases below, APAC is assumed to capture ~30–40 % of global PtL by 2050. The numbers sit within the wide spread in published outlooks[5].

- **Lower range:** ~20–30 Mt/y PtL by 2050, based on SkyNRG's SAF Market Outlook[4] (Asia ≈ 70 Mt SAF).
- **Upper bound:** up to ~55 Mt/y PtL by 2050, consistent with ATAG Waypoint 2050[2] .

Table 8 summarises the indicative resource requirements for each case, providing a high-level view of the electricity, CO_2, hydrogen and water needed to support 20–30 Mt/y versus up to 55 Mt/y of PtL in APAC by mid-century.

TABLE 8 INDICATIVE RESOURCE REQUIREMENTS FOR PTL DEPLOYMENT IN APAC BY 2050 UNDER TWO ILLUSTRATIVE SCENARIOS

Values cover electricity, hydrogen, water and CO_2 inputs. Platinum and iridium are excluded due to technology dependence and expected efficiency gains.

RESOURCE	INDICATIVE LOWER-RANGE (20-30 MT/Y)	INDICATIVE UPPER-BOUND (55 MT/YR)	COMPARATOR	COMMENT
Electricity	500-1,200 TWh/y	1,400-2,100 TWh/y	≈15,000 TWh = today's APAC generation62	Equivalent to about 3–14 % of today's APAC electricity generation (≈15,000 TWh/y).
Hydrogen	8.5-17 Mt/y	24-31 Mt/y	≈95 Mt = today's global H_2 production (fossil-based)	Equivalent to roughly 9–33 % of today's global hydrogen production (≈95 Mt/y).
Deionised water	0.15 – 0.35 bn m³/y	0.35 – 0.65 bn m³/y	Annual water use of 2.5 -7 million people (≈50 m³/ person/yr)	Comparable to the annual water use of around 3–13 million people.
Seawater intake	0.25 – 0.7 bn m³/y	0.7 – 1.30 bn m³/y	≈0.365 bn m³/yr = intake of one 1-million m³/day desalination plant.	Similar to the intake of roughly 1–4 large desalination plants (≈1 million m³/day each)
CO_2 inputs	60 – 120 Mt CO_2/y	170 – 215 Mt CO_2/y	≈Australia's annual energy-related CO_2 emissions (~400 Mt CO_2/yr)	Corresponds to about 15–55 % of Australia's annual energy-related CO_2 emissions (≈400 Mt CO_2/y).

The stress test illustrates the scale of inputs if APAC were to produce 20–30 Mt/y PtL or ~55 Mt/y PtL by 2050. Even in the moderate case, *requirements are substantial*:

- **Electricity is the dominant constraint.** Delivering 20–30 Mt/y would use about 3–8 % of today's APAC power generation (≈15,000 TWh), while ~55 Mt/y rises to ~9–14 %—implying unprecedented renewable build-out and major grid integration efforts.
- **Hydrogen scales with electricity.** Totals reach 8.6–16.8 Mt/y H_2 (moderate) and 23.6–30.8 Mt/y (high)—roughly ~9–18 % and ~25–32 % of today's global hydrogen production (≈95 Mt, mostly fossil-based). Meeting this requires multi-GW electrolyser deployment coordinated with renewable power.
- **Water requirements are moderate but location-sensitive.** Deionised water for electrolysis totals ~0.12–0.35 bn m³/y (moderate) and ~0.33–0.63 bn m³/y (high). If desalination is used, seawater intake ≈ 2× DI—i.e., ~0.24–0.69 bn m³/y and ~0.66–1.27 bn m³/y, respectively—on the order of ~0.7–3.5 large desalination plants (1 million m³/day each). Siting and discharge management matter in water-stressed coastal regions.
- **CO_2 feedstock becomes binding at scale**. PtL would require ~60–117 Mt CO_2/y (moderate) to ~165–215 Mt CO_2/y (high)—comparable to a sizeable national emissions footprint (e.g., Australia ~400 Mt CO_2/yr). Early volumes can draw on industrial/biogenic point sources; by mid-century, large-scale DAC is likely needed, adding further electricity demand.
- **Raw materials — pressures to watch.** Needs depend on electrolyser choice and plant design, so we discuss them qualitatively here. Iridium is the most pressing bottleneck under a PEM baseline (global supply ≈10 t/yr, scaling with hydrogen output). Platinum also matters for PEM (market larger than Ir but still sensitive). If alkaline electrolysis (AEL) grows, Ir/Pt requirements fall while nickel rises; copper tracks electrical balance-of-plant; SOEC shifts needs toward ceramic/specialty components.

4.2. RESOURCE AVAILABILITY IN APAC

This section turns from what is needed and the scale markers from the stress test (Section 4.1) to what is available in APAC. We screen renewable-electricity capacity and provide high-level availability mappings for green hydrogen, CO_2, water, biomass residues, and critical raw materials across selected countries. For a one-page roll-up of findings and implications, see the consolidated summary in Section 4.2.4.

4.2.1. Renewable Electricity Capacity Screening

Renewable electricity is the primary input to PtX fuels. We therefore built a simple country scorecard (10 indicators; see **Table 9**) to compare how ready eight APAC countries are to scale clean power for PtX[a]. The indicators sit in three plain buckets:

- **Deployment momentum:** current penetration of renewables, near-term growth trajectories (2030 projections, annual additions), and financial commitment (clean energy investment relative to GDP).
- **Resource potential:** the underlying availability of renewable energy resources, measured by solar irradiation, wind speeds, and hydropower capacity, which together account for the vast majority of regional renewable potential. Geothermal resources, while locally important in countries such as Indonesia, the Philippines, Japan, and New Zealand, are not included in the indicator set due to limited data comparability, but are recognised qualitatively as valuable complementary sources[b].
- **System readiness:** indicators of how effectively renewable electricity can be integrated, including average capacity factors, national policy targets, and grid integration maturity.

The indicators combine absolute values (e.g. current installed RE capacity) with relative measures (e.g. share of electricity from renewables, growth compared to today, investment intensity), ensuring comparability across countries of very different sizes. Detailed thresholds and data sources are provided in Annex IV.

The results (**Table 9**) offer a comparative view of renewable electricity readiness across the selected countries, highlighting both structural strengths and bottlenecks that will shape PtX fuel deployment in APAC. These readiness levels also reflect long-term system path dependencies: countries with long-established fossil export models (e.g. Australia), large domestic coal bases (e.g. China, India), or historically import-dependent systems (e.g. Japan, South Korea, Singapore) face different structural challenges and opportunities in scaling renewable power for PtX.

a. The scorecard assesses renewable-readiness indicators only. It does not evaluate overall power-mix trajectories or fossil build-out (e.g., new coal capacity in India or China). Those trends matter for climate impact, but are out of scope for this screening.
b. For completeness, geothermal resources in these countries could contribute an additional ~60–100 TWh per year of renewable electricity by 205063,64. This represents only a small share of the region's total renewable potential compared with solar, wind, and hydropower.

TABLE 9

RENEWABLE ELECTRICITY (RE) CAPACITY CLASSIFICATION IN SELECTED APAC COUNTRIES, GROUPED INTO DEPLOYMENT MOMENTUM, RESOURCE POTENTIAL, AND SYSTEM READINESS.

	DEPLOYMENT MOMENTUM								RESOURCE POTENTIAL			SYSTEM READINESS			
COUNTRY	CURRENT INSTALLED RE CAPACITY (GW)	CURRENT SHARE OF LOW-CARBON ELECTRICITY (%)	2030 PROJECTION FOR RE CAPACITY (GW)	% INCREASE TO CURRENT CAPACITY	ANNUAL ADDITION OF RE CAPACITY (GW/YEAR)	% INCREASE TO CURRENT CAPACITY	INVESTMENT IN CLEAN ENERGY (USD/YR)	% OF GDP	SOLAR (KWH/KWP)	WIND (M/S)	HYDRO (GW)	CAPACITY FACTOR (%)	NATIONAL TARGETS (%)	GRID INTEGRATION PHASE	TOTAL RE CAPACITY SCORE
Australia	45	36	100	122	4	9	6	0.35	5	7	8	30	82	5	High
China	1200	35	3000	150	150	13	90	0.53	4.3	7.5	420	45	90	5	Very High
India	180	20-22	500	178	10	6	20	0.54	4.8	6.5	50	35	50	4	High
Japan	110	26	150	36	5	5	10	0.24	3.6	6	20	25	36	4	Medium
Malaysia	10	3-19	20	100	0.8	8	2	0.44	4.2	5.8	6	18	31	3	Low
Singapore	2	3	5	150	0.2	10	0.5	0.1	3.8	4.5	0.1	12	/	2	Very Low
South Korea	30	9	90	200	2	7	3	0.18	3.5	6.2	9	22	30	3	Low
Thailand	30	5-10	100	233	3	10	3	0.6	4.5	6	18	25	30-35	3	Medium

Capacity scoring classification: Very High, High, Medium, Low, Very Low

The screening highlights wide differences in renewable-electricity readiness across APAC. **China** scores *Very High*, reflecting its exceptional installed base, rapid annual additions, strong policy commitments, and a diversified wind–solar–hydro mix. *Australia* and *India* score **High:** both combine strong resource potential with clear growth trajectories, though India must integrate large volumes from a relatively low current share.

Japan and **Thailand** are **Medium**. Japan pairs ambitious targets and high investment intensity with tighter domestic resource potential; Thailand shows balanced progress but faces grid-flexibility constraints. **Malaysia** and **South Korea** are **Low**, limited by modest annual additions, lower renewable shares today, and weaker system readiness. **Singapore** ranks **Very Low** due to structural land constraints despite good solar performance—its pathway will likely rely on regional cooperation and imports.

Overall, readiness is shaped as much by deployment momentum and system integration as by natural resource potential. Countries with strong endowments but slow build-out (e.g., Malaysia) face constraints similar to land-limited systems (e.g., Singapore). By contrast, systems that align resource potential, policy ambition, and grid readiness (China, Australia, India) are best placed to support PtX at scale. These patterns also reflect long-standing path dependencies—from fossil-export legacies to large coal fleets and import-dependent power systems—which help explain the pace and direction of PtX deployment prospects across the region.

Electricity Continuity and Certification Requirements

The capacity screening indicates where renewable electricity can grow, but PtX plants also require continuous, certifiable power (see Section 5.4). Solar and wind are variable, so usable power depends on grid flexibility and on meeting certification criteria such as additionality, temporal correlation (hourly matching), and geographic proximity.

Australia and India have strong growth potential, yet meeting hourly correlation at scale will still require storage, hybrid portfolios (wind/solar backed by hydro where available), and targeted grid upgrades. China, which scored "Very High," benefits from a more diversified mix and more advanced integration measures; this reduces curtailment, improves continuity, and makes alignment with certification requirements more straightforward.

Malaysia, South Korea, and Singapore face compounded challenges: limited space for new renewables, slower additions, and tighter system flexibility. In these systems, meeting additionality and hourly matching will be difficult without regional cooperation, imports, or dedicated off-grid projects. Japan and Thailand sit in the middle: both have credible targets and investment, but they will need further grid reinforcement and flexibility solutions to manage intermittency and comply with hourly matching under schemes such as EU RED III and RSB.

In summary, the screening is a first cut at renewable potential; whether that potential can be delivered as certification-eligible, temporally correlated electricity depends on storage, hybridisation, and grid integration, and will vary by country context.

4.2.2. Green Hydrogen Availability Screening

While renewable electricity forms the backbone of PtX fuel production, green hydrogen is the critical intermediate that enables the synthesis of PtX fuels. This sub-section provides a high-level screening of green hydrogen availability across selected APAC countries. The analysis focuses on production potential and reported capacities; detailed modelling of transport, storage, and associated availability constraints is beyond the present scope.

Unlike renewable electricity, green hydrogen data is less standardised and more speculative, especially for long-term projections. Most capacity estimates are based on announced projects, national roadmaps, and strategic targets rather than operational infrastructure. As such, this screening focuses on indicative ranges for current and projected production capacities, drawing from the IEA Hydrogen Projects Database[65], national hydrogen strategies, and other reputable sources.

Table 10 summarises estimated green hydrogen capacities for 2024 and 2030, along with qualitative notes on each country's strategic positioning, infrastructure readiness, and role in regional hydrogen trade.

TABLE 10 GREEN HYDROGEN AVAILABILITY SCREENING IN SELECTED APAC COUNTRIES

COUNTRY	2024 CAPACITY (KT H_2/YR)	2030 CAPACITY RANGE (KT H_2/YR)	NOTES	REF.
Australia	~500–1,000	10,000–20,000	Australia is a global frontrunner with massive electrolyser projects planned. Export-oriented strategy targeting Japan, South Korea, and Europe. Strong government support and abundant renewables.	66
China	~1,800	10,000–20,000+	China leads in installed electrolyser capacity and project pipeline. Strong industrial demand and policy support. Focus on decarbonizing steel, chemicals, and transport.	66
India	~100–500	5,000–8,000	India's National Green Hydrogen Mission targets 5 Mt/year by 2030. Focus on domestic use in refining, fertilizers, and mobility. Large-scale solar and wind integration planned.	66
Japan	~2.2	5–10	Japan has limited domestic production and focuses on importing hydrogen from countries like Australia and Brunei. Domestic capacity remains modest, with government support for hydrogen hubs and fuel cell vehicles.	66
Malaysia	~0	2,000–2,500	Malaysia's Hydrogen Economy and Technology Roadmap (HETR) targets 2 Mt/year by 2030 and 16 Mt/year by 2050. Focus on solar and hydropower-based hydrogen, with export ambitions to Japan and South Korea.	67, 68
Singapore	~0	15–25	Singapore is positioning itself as a hydrogen trading hub with limited domestic production due to land constraints. Focus is on imports and bunkering infrastructure.	66
South Korea	~0	200–300	South Korea is scaling up rapidly, aiming for 3 Mt/year by 2050. Domestic production is supported by strong policy frameworks and infrastructure development, including hydrogen buses and refueling stations.	66
Thailand	~0	100–300	Thailand's hydrogen strategy focuses on blending hydrogen into gas grids and using it in transport and industry. Pilot projects underway; full-scale adoption expected post-2030.	69, 70

The screening shows that green hydrogen development in APAC is progressing unevenly. Australia, China, and India show strong potential for large-scale production, driven by abundant renewables and national strategies. Japan, South Korea, and Singapore are likely to rely on imports, while Malaysia and Thailand are emerging players with growing interest but limited current capacity. Compared to renewable electricity, hydrogen data is less mature and more uncertain, making this screening a directional overview rather than a definitive assessment.

As in 4.3.1, it should be noted that certifiable green hydrogen depends not only on overall renewable capacity but also on temporal and geographic matching of inputs, aspects that are highlighted qualitatively rather than modelled in this study. Meeting these requirements typically implies storage, hybridisation, or imports from regions with surplus renewable supply.

Green Hydrogen Deployment Challenges in APAC

Green hydrogen deployment across APAC faces a range of structural and economic challenges that are slowing progress and leading to project cancellations. While Australia has seen some of the most visible setbacks, including the cancellation of the flagship CQ-H_2 export project and retrenchment by Fortescue and Origin Energy[71,72], similar issues are emerging across the region.

Key challenges include:

- **High production costs:** Electrolysis remains expensive, and inflationary pressures have made many projects financially unviable without subsidies[72].
- **Weak demand signals:** Developers struggle to secure binding offtake agreements, especially for export-oriented projects, leading to delays or cancellations[73].
- **Infrastructure and permitting hurdles:** Large-scale hydrogen projects require extensive approvals, land, water, and grid access, which are often difficult to secure in Southeast Asia and India[72].
- **Policy fragmentation:** The lack of harmonized certification and regulatory frameworks across APAC complicates cross-border trade and investment[74].

According to recent studies[73,74], countries like India, China, and Southeast Asian economies also face challenges in aligning policy ambition with market readiness. Many announced projects remain in early development stages, and only a fraction have reached financial close . These challenges suggest that while APAC holds immense potential for green hydrogen, realising it will require coordinated policy support, infrastructure investment, and realistic market strategies tailored to each country's context.

Overall, the uneven progress and high cost of green-hydrogen production underline its dual role as both an enabler and a bottleneck for PtX fuel deployment in APAC. While renewable-electricity supply remains the first-order constraint, hydrogen-production capacity and infrastructure readiness will ultimately determine whether this renewable potential can be converted into scalable PtL and PBtL pathways. Coordinated policy frameworks, regional trade mechanisms, and investment de-risking will therefore be critical to translating current ambitions into operational capacity.

4.2.3. Availability of Complementary Resources for PtX fuels

Beyond renewable electricity and green hydrogen, the feasibility of PtX fuel production depends on other critical resources: CO_2 (carbon feedstock for PtL), biomass residues (carbon feedstock for PBtL), water (primarily for electrolysis), and critical raw materials (for electrolysers and renewable-power equipment). This section provides a high-level screening of these resources across selected APAC countries.

Compared with electricity and hydrogen, data coverage for these resources is more uneven and reported under differing boundaries. For example, CO_2 sources—especially biogenic streams—are not always compiled consistently across inventories; water stress datasets vary in spatial granularity; biomass residue estimates depend on agricultural statistics and collection assumptions; and raw-material figures often reflect mining or refining capacity but not processing bottlenecks or export constraints. Given these caveats, the screening uses *indicative ranges* and a *five-tier, colour-coded classification* to show relative favourability—rather than precise project-level quantities—and to highlight potential strengths and bottlenecks by country.

Screening of CO_2 and Water Resources

Table 11 presents a comparative overview of industrial CO_2 availability, biogenic CO_2 potential, renewable freshwater resources per capita, and seawater desalination capacity across selected APAC countries. These resources are essential inputs for PtX fuel production, particularly for CO_2 hydrogenation and electrolysis processes. The screening applies a five-tier availability classification, ranging from Very High to Very Low, to compare the relative abundance of industrial and biogenic CO_2 sources and freshwater or desalination potential across countries. The classification does not reflect economic or environmental quality but rather the indicative availability of these resources for PtX fuel production.

- **Industrial CO_2 availability** is estimated based on national greenhouse gas inventories and sectoral emissions data from the IEA CCUS Projects Database[90,9]. It includes emissions from cement, steel, chemicals, and power generation. China and India show very high availability due to their large industrial bases, while Australia, Japan, and Malaysia offer moderate-to-low volumes concentrated around specific industrial clusters. Singapore and South Korea have limited industrial sources due to smaller industrial footprints.

- **Biogenic CO_2 availability** includes emissions from bioethanol fermentation, biomass cogeneration, biogas upgrading, and waste-to-energy facilities. Data are based on IEA Bioenergy Task 39[75] and regional sectoral estimates. Countries with active bioethanol and bioenergy industries, such as India, Thailand, Malaysia, and Indonesia, show moderate potential, while Japan, South Korea, and Singapore remain low. These sources are generally of high purity but spatially dispersed, and their capture potential will depend on scale, logistics, and regulatory recognition under CORSIA.

- **Direct Air Capture (DAC):** DAC is currently marginal in APAC and not included in **Table 10** due to its nascent scale. Globally, DAC remains limited, just 27 plants capturing ~0.01 Mt CO_2/year currently in operation[76,77]. In Asia, China has tested a "CarbonBox" module (~600 t/yr)[78], and Japan recently announced its first commercial DAC installation[79]. Most DAC in practice today in APAC is linked to enhanced oil recovery (EOR) applications rather than fuel synthesis[80]. Despite this early stage, DAC represents a critical future enabler: APAC's industrial and biogenic CO_2 sources alone will be insufficient to meet long-term PtX fuel demand. As highlighted in the stress-test analysis (Section 4.2), large-scale DAC deployment will be instrumental beyond 2040 to close the CO_2 supply gap and ensure sustainable, verifiable carbon sourcing for PtX fuel pathways.

- **Renewable freshwater resources per capita** are sourced from FAO AQUASTAT and World Bank datasets[81–83]. Availability varies significantly across the region: Australia and Malaysia benefit from high renewable freshwater resources due to favorable climate and low population density, whereas India, China, and South Korea experience growing water stress, and Singapore faces severe scarcity. These differences imply local siting and cost implications for electrolysis-based hydrogen production.

- **Seawater desalination capacity**, based on combined municipal and industrial data from the World Population Review (2024)[84] and the Powerfuels Status & Prospects (2024)[40] report, varies widely. China and Singapore have the most advanced desalination infrastructure—both scaling rapidly to meet industrial and municipal demand. Australia and India follow with significant but unevenly distributed capacity. In contrast, Japan, South Korea, Malaysia, and Thailand maintain limited or pilot-scale installations. Reported figures differ substantially across literature due to differences in reporting boundaries (municipal vs. industrial plants) and data years; therefore, indicative ranges are used for comparability.

TABLE 11 INDICATIVE FAVORABILITY OF INDUSTRIAL AND BIOGENIC CO_2 SOURCES AND WATER AVAILABILITY (FRESHWATER AND DESALINATION) IN SELECTED APAC COUNTRIES

	CO_2 SOURCING			WATER SOURCING		
COUNTRY	INDUSTRIALY CO_2 AVAILABILITY (MT CO_2/YR)	BIOGENIC CO_2 AVAILABILITY (MT CO_2/YR)	TOTAL SCORING - CO_2 SOURCES	RENEWABLE FRESHWATER RESOURCES PER CAPITA (M^3)	SEAWATER DESALINATION CAPACITIES (MM^3/DAY)	TOTAL SCORING - WATER SOURCES
Australia	25–35	2–5	Favorable	~20,000	~1.6	Very Favorable
China	100-120	10–20	Very Favorable	~2,000	~9.7	Medium
India	50-70	5–10	Favorable	~1,500	~2.9	Unfavorable
Japan	15–25	<1	Unfavorable	~3,000	~0.2-0.3	Moderate
Malaysia	10-20	3-6	Favorable	~18,000	~0.05-0.1	Favorable
Singapore	<1	<0.1	Very Unfavorable	~100	~0.9-1.0	Moderate
South Korea	10–15	<1	Unfavorable	~2,000	~0.1-0.2	Unfavorable
Thailand	10-15	3-6	Very Favorable	~4,000	<0.05	Favorable

Scoring classification: Very Favorable, Favorable, Moderate, Unfavorable, Very Unfavorable

Screening of Biomass Residue Resources

Table 12 presents a comparative overview of biomass residue availability across selected APAC countries. Biomass constitutes a key biogenic feedstock for PBtL (hybrid PtX–biomass pathways), where renewable hydrogen is combined with carbon-rich residues to produce synthetic fuels. These routes are particularly relevant in contexts requiring biogenic CO_2 or syngas inputs.

The screening focuses on *low-ILUC, residue-based feedstocks*, consistent with Section 3.2.4 and international sustainability frameworks such as ICAO CORSIA, EU RED II/III, and RSB Global (Standard). It includes agricultural residues (e.g. sugarcane bagasse, rice and cereal straw, corn stover, and cassava residues), palm-oil residues, municipal solid waste (MSW), and forestry by-products.

While *certain dedicated low-ILUC energy crops* (e.g. perennial grasses or short-rotation coppice) could complement these resources in the future, they are not quantified here due to limited data and the study's emphasis on existing, readily quantifiable residues and wastes. Because reporting remains fragmented, **Table 11** applies indicative order-of-magnitude ranges and a five-tier favourability scale to indicate relative suitability for PBtL applications rather than precise tonnage estimates.

Feedstock-specific observations

- **Sugarcane bagasse[48,85]:** Indicative ranges of 0–80 Mt yr^{-1} were found, with **India, Thailand, and China** as major producers. Bagasse, a fibrous by-product of sugar milling, is already widely utilised for co-generation but retains further potential for syngas production in hybrid PtX systems.

- **Rice straw and residues[47]:** Availability spans 0–150 Mt yr^{-1}, with **India, China, Thailand, and Indonesia** as leading sources. Rice straw is often burned due to limited collection logistics but represents a major sustainable carbon source for biofuels and biochar valorisation.

- **Wheat and barley straw:** New to this assessment, cereal straw residues in **Australia, China, and India** collectively exceed 25–150 Mt yr^{-1}. These residues are particularly relevant in broadacre systems and enhance overall residue availability in temperate and semi-arid regions.

- **Palm-oil residues[48]:** Around 0–40 Mt yr^{-1} (dry basis), dominated by **Indonesia and Malaysia**, with smaller volumes in Thailand. Key solids include empty-fruit bunches (EFB), mesocarp fibres, and palm kernel shells—rich in organics yet still underutilised for energy. Liquid by-products such as POME are excluded, as they are primarily used for biogas recovery.

- **Corn stover**: Estimated at 0–300 Mt yr^{-1} across the region, with the largest resources in **China and India**, followed by Thailand and Indonesia. These residues represent an important seasonal complement to rice- and wheat-derived residues.

- **Municipal solid waste (MSW)[47,85]:** Generation ranges from 0–100 Mt yr^{-1}, concentrated in **China, India, Indonesia, and Japan**. Roughly 40–60 % of MSW is biogenic (food, paper, yard waste) and relevant for PtX pathways, depending on segregation and collection efficiency.

- **Cassava processing residues[48]:** 0–20 Mt yr^{-1}, with **Thailand, Malaysia, and Indonesia** as main producers. Peels and pulp from cassava starch processing are increasingly valorised for composting, animal feed, or biochar, and represent a viable local feedstock for carbon recovery.

- **Forestry residues (sawmill wastes)[85,86]:** Estimated at 0–50 Mt yr^{-1}, with notable volumes in **Australia, China, Indonesia, and Malaysia**. These include sawdust, bark, and trimmings; recovery potential depends on mill technology and forestry practice.

TABLE 12 INDICATIVE AVAILABILITY OF BIOMASS RESIDUES RELEVANT FOR PBTL PATHWAYS IN SELECTED APAC COUNTRIES (DRY MASS, MT YR^{-1}).

COUNTRY	BIOMASS (MT/YEAR) DRY MASS								TOTAL SCORE
	SUGARCANE BAGASSE	RICE STRAW/ RESIDUES	WHEAT AND BARELY STRAW	PALM OIL RESIDUES	CORN STOVER	MSW	CASSAVA RESIDUES	FORESTRY RESIDUES	
Australia	~5	~10	~25-35	<1	~1-3	~20	<1	~30	Favorable
China	~60	~150	~120-150	~5	~200-300	~100	~5	~25	Very favorable
India	~80	~120	~80-120	~5	~30-60	~90	~10	~20	Very favorable
Indonesia	~10	~50	<1	~40	~5-10	~85	~4	~25	Favorable
Japan	<1	<1	~2-4	<1	~1-3	~40	<1	~10	Unfavorable
Malaysia	~10	~15	<1	~25	~1-2	~15	~10	~10	Favorable
Singapore	<1	<1	<0.1	<1	<0.1	~10	<1	<1	Very unfavorable
South Korea	<1	<1	~2-3	<1	~1-2	~30	<1	~5	Unfavorable
Thailand	~40	~60	<1	~5	~8-12	~20	~15	~10	Very favorable

Scoring classification: Very favorable; Favorable; Moderate; Unfavorable; Very unfavorable

Screening of Raw Material Resources

This section presents a comparative overview of critical raw material availability and refining capacities across selected APAC countries. These materials are essential for PtX fuel pathways, particularly in the manufacture of electrolysers, catalysts, and fuel-synthesis systems.

While Section 4.1 (**Table 7**) quantifies core process resources such as electricity, hydrogen, water, and CO_2, **Table 13** screens the availability of critical raw materials essential for PtX fuel systems — particularly those required for electrolyser, catalyst, and synthesis-unit manufacturing — and also includes enabling and structural materials (e.g. iron, steel, chromium, titanium, zinc) that underpin wider PtX and renewable-energy infrastructure[56].

Data for this screening were compiled from leading international databases and institutional sources, including the European Commission's Raw Materials Information System (RMIS)[87–90], the U.S. Geological Survey's Mineral Commodity Summaries 2024[91], the International Energy Agency's Critical Minerals Market Review 202392, and the ASEAN Minerals Cooperation Portal[93].

These sources provide the most consistent and up-to-date information on mining and refining capacity across the APAC region. National data were cross-checked where available, but some gaps remain due to inconsistent reporting and differing definitions of "refining" across countries. Where quantitative information was unavailable or inconsistent, qualitative classifications were applied based on the latest verified industry data. These limitations are most evident in rapidly evolving segments, notably Indonesia's expanding nickel and cobalt refining capacity and China's continued dominance in metal refining for PtX-related applications.

The assessment applies indicative global share ranges and a unified four-tier scoring scheme (High ≥ 20–25 %; Medium ≈ 5–20 %; Low ≈ 1–5 %; Very Low < 1 %) to categorise each country's relative role in mining and refining. Blank cells denote no known activity or insufficient data.

TABLE 13 SCREENING OF RAW MATERIAL RESOURCES: PRIMARY PRODUCTION AND REFINING CAPACITIES IN SELECTED APAC COUNTRIES (2023–2024)

Countries are classified by colour based on their estimated global share of raw material resources: green = high (>20-25 %), yellow = medium (5-20 %), orange = low (1-5 %), grey = very low/negligible (<1 %), no colour = no known activity or no data available.

Blank fields indicate there are no known activities or no reliable data. Final overall country scores are then derived and classified by colour: dark green = very high, green = high, yellow = medium, orange = low, red = very low.

	RAW MATERIAL																
	CHROMIUM		COBALT		COPPER		IRON / STEEL		NICKEL		PLATINUM-GROUP METALS	TITANIUM		ZINC		TOTAL SCORE
INDICATOR	Primary	Refining	Primary	Refining	Primary	Refining	Primary	Refining (Steel)	Primary	Refining	Primary / Refining	Primary	Refining	Primary	Refining	
Australia	orange	orange			yellow	yellow	dark green	yellow		orange	Minimal primary production in APAC; refining and recycling limited in Japan and China; major supply from South Africa / Russia.	dark green	yellow	yellow	yellow	green
China	yellow	dark green	grey	dark green	dark green	dark green	dark green	dark green	orange	dark green		dark green	dark green	dark green	dark green	green
India	orange	orange			yellow	yellow	dark green	yellow				yellow	yellow	yellow	yellow	yellow
Indonesia			yellow	yellow	yellow	yellow	orange	orange	dark green	dark green		orange	grey			yellow
Japan						orange		yellow								orange (low)
Malaysia	grey		grey			grey	orange	orange		grey			grey	orange	grey	orange (low)
Singapore																red (very low)
South Korea						orange		orange								orange (low)
Thailand	grey				orange	grey	yellow	yellow						orange	grey	yellow

Key findings and highlights

- **Nickel:** Indonesia remains the dominant global primary producer, contributing roughly 50 % of global nickel mine output, with rapidly expanding refining capacity through High-Pressure Acid Leaching (HPAL) and Nickel Pig Iron (NPI) projects. China retains a major role in nickel refining (~ 35 %), while Australia and China each maintain medium mining shares.

- **Cobalt:** Global refining is heavily concentrated in China (> 70 %), while Indonesia has emerged as a growing primary producer (~ 7–8 %) and medium refiner. Other APAC countries have negligible extraction or refining capacity.

- **Copper[1]:** China dominates regional mining and refining, accounting for a high share (> 25 %) of refined copper output. Australia and India have medium mining shares, while Japan, South Korea, and Malaysia operate small-scale refining linked to alloy and electronics industries.

- **Iron / Steel:** Australia, China, and India collectively dominate global iron ore and steel production, with China as the world's largest steel producer. Indonesia, Thailand, and Malaysia maintain low to medium shares, serving mainly regional markets.

- **Chromium:** China and India are the only significant APAC producers and refiners, while most other countries show very low or no activity, as production is largely tied to ferrochrome and stainless-steel industries.

- **Titanium:** Australia and China lead global titanium and ilmenite output, with India holding a medium share. Other countries, including Indonesia, Malaysia, and Thailand, report very low activity.

- **Zinc:** China remains the world's leading zinc miner and refiner (> 30 % global share), while Australia and India contribute medium shares. Southeast Asian countries have minor or negligible roles.

- **Platinum-group metals (Pt, Ir, etc.):** No major primary production occurs within APAC; refining and recycling are limited to Japan and China, with supply largely imported from South Africa and Russia.

Overarching Conclusions from Complementary Resource Screenings

The complementary screenings for CO_2, water, biomass residues, and critical raw materials (CRMs) confirm that the suitability of resource bases for PtX fuel deployment in APAC is highly uneven and pathway-specific. While the region holds significant aggregate resource potential, availability, accessibility, and sustainability vary sharply across geographies and sectors. Electricity and hydrogen remain the primary enablers that set the overall scale ceiling; complementary resources shape where and how fast projects can proceed.

In contrast, the complementary screenings show that:

- **CO_2 sources** remain dominated by industrial point emissions in China and India, offering short-term supply but raising sustainability and traceability concerns. Biogenic CO_2 is available mainly in India, Thailand, and Malaysia, but at limited scale, and DAC capacity in APAC remains negligible—currently linked mostly to enhanced oil recovery pilots. Scaling DAC will be essential beyond 2040 to ensure long-term carbon integrity and certification compliance.

- **Water resources** are regionally constrained and unevenly distributed. Inland areas such as India and northern China face chronic water stress, while Australia and Malaysia benefit from abundant renewable freshwater. Desalination, where powered by renewables, provides a viable mitigation pathway in coastal and arid economies (e.g. Singapore, Australia), although capacity estimates vary widely across sources.

- **Biomass residues** are abundant but highly fragmented. Major volumes exist in India, Indonesia, and Thailand, while Japan, Korea, and Singapore show negligible availability. Feedstock mobilisation faces logistical, sustainability, and land-use trade-offs, but agricultural residues and wastes remain key near-term enablers for PBtL and hybrid PtX routes.

- **Critical raw materials (CRMs)** essential for electrolysers and catalysts (nickel, cobalt, platinum-group metals) are strongly concentrated in a few countries—China, Australia, and Indonesia—creating medium-term supply-chain and ESG exposure risks. Japan and South Korea play complementary roles through refining and recycling capacity, but overall dependency remains high.

4.2.4. Consolidated Summary of PtX Fuel Resource Availability in APAC

This section provides an integrated overview of the key resource dimensions underpinning PtX fuel production potential across the APAC region. Building on the country-specific assessments presented in Sections 4.2.1 to 4.2.3, it consolidates findings on renewable electricity capacity, water availability, carbon sources, biomass resources, and critical raw materials. Together, these factors determine the technical feasibility and sustainability of PtL and PBtL pathways within each national context.

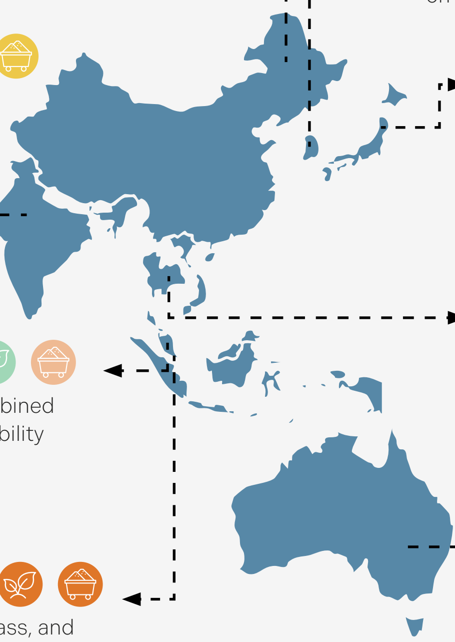
Figure 6 presents a comparative visualisation of relative resource availability across selected APAC countries, using a colour scale from very high (dark green) to very low (red). The figure also summarises, in short country notes, the dominant resource strengths and constraints that shape each country's PtL and/or PBtL potential.

China
Exceptional renewable and material capacity gives China the strongest PtL and PBtL resource base across APAC, though regional water stress requires attention.

South Korea
Constrained renewable and biomass resources limit domestic PtL and PBtL production; relies on imported energy and materials.

India
High renewable and biomass availability underpin significant PtL and PBtL potential, but freshwater scarcity is a major constraint.

Japan
Limited renewable capacity and biomass reduce domestic PtL and PBtL potential; good water access offers some flexibility for smaller projects.



Thailand
Balanced renewable and biomass availability enables notable PBtL opportunities, though water stress could restrict large-scale PtL development.

Malaysia
Moderate renewable potential combined with high water and biomass availability could support PBtL development if renewable capacity expands.

Australia
Very high renewable capacity and strong raw-material base support large-scale PtL and PBtL potential. Water availability can be managed through desalination.

Singapore
Extremely limited renewable, biomass, and carbon sources result in minimal domestic PtL or PBtL potential; depends fully on imports.

Renewable Electricity Capacity:

Electricity used for PtX fuel production must comply with certification criteria ensuring additionality, temporal correlation, and sustainable sourcing.

Ensuring continuous, low-carbon electricity supply is key to sustainable PtX operations and system efficiency

Water Sources:

Water use must avoid exacerbating freshwater stress and follow strict sustainability criteria, including catchment-level risk assessment.

Renewable-powered seawater desalination and wastewater reuse are preferred options to ensure reliable, low-impact supply.

Carbon Sources (for PtL Fuels):

Transitional use of unavoidable industrial point-source CO_2 is permissible under strict temporal and additionality conditions.

Biogenic CO_2 is the preferred sustainable source today, while DAC must scale rapidly to meet future carbon demand.

Raw Materials:

Critical minerals and materials for electrolysers and renewables must be sourced under strong environmental and social due diligence frameworks.

Recycling, circular use, and responsible supply-chain practices are essential to reduce upstream impacts and regional inequalities.

Biomass (for PBtL Fuels):

Sustainable biomass should prioritise wastes, residues, and low-ILUC feedstocks consistent with international sustainability standards.

Dedicated low-ILUC energy crops are eligible under certification but excluded from the quantitative availability screening.

FIGURE 6 **PTX FUEL RESOURCE AVAILABILITY ACROSS SELECTED APAC COUNTRIES**

PtX fuel resource availability across selected APAC countries, highlighting relative strengths in renewable capacity, water, carbon, biomass, and raw materials that underpin PtL and PBtL potential, based on findings of this study.

The figure classifies the estimated resource availability by colour: dark green = very high, green = high, yellow = moderate, orange = low, dark orange = very low.

4.3. RESOURCE COMPETITION AND TRADING POTENTIALS

Resource competition and sectoral dynamics

The expansion of PtX fuel production in the APAC region depends not only on the physical availability of resources (see Section 4.2) but also on the degree of competition with other sectors. This section focuses on three key resources where sectoral competition is already visible or expected to intensify: renewable electricity, captured CO_2, and green hydrogen. Brief notes are also provided on biomass, critical raw materials, land, and water.

Renewable electricity: Renewable electricity is the foundational input for PtX and PtX fuel production, powering electrolysis, direct air capture (DAC), and fuel synthesis. Yet it is also the backbone of wider economy-wide decarbonisation.

Current data from the IEA[94] show that industry and commercial/public services dominate renewable electricity consumption across APAC, each absorbing more than one-third of allocations in countries such as Japan, South Korea, China, and Australia (see **Table 14**). Residential demand is also notable, especially in rooftop-PV-driven markets like Japan, Singapore, and Australia.

Competition is expected to intensify in several sectors[94–96]:

- **Industry** will remain the largest consumer as electrification of heat and industrial processes accelerates[95].
- **Transport** demand will grow strongly with the rise of electric vehicles and indirect electrification via synthetic fuels.
- **Commercial and digital infrastructure** (including data centres) will expand rapidly, adding pressure on renewable supply, though precise data remain uncertain.

Meanwhile, agriculture and forestry uses will likely stay stable, driven mainly by off-grid and seasonal needs.

It is important to note that not all renewable electricity reported in national statistics is available for PtX fuel production (see Section 5). Certification frameworks require additionality, meaning electricity must come from new or dedicated renewable capacity rather than existing grid renewables. As shown in Section 4.2.1, the scope for renewable capacity expansion differs markedly across APAC countries, which limits how much power can realistically be allocated to PtX. While large SAF offtakes can stimulate new investment, these rules are binding; PtX deployment ultimately depends on sustained, long-term renewable build-out beyond baseline national targets.

TABLE 14 CURRENT RENEWABLE ELECTRICITY END-USE SHARES BY SECTOR IN SELECTED APAC COUNTRIES.

Current renewable electricity end-use shares by sector in selected APAC countries. Percentages indicate the share of renewable electricity in total sectoral consumption. Colour intensity reflects the magnitude of the share: darker green corresponds to higher percentages. The right-hand column indicates expected trends in competition[94–96].

RENEWABLE ELECTRICITY END USE	AUSTRALIA	CHINA	INDIA	JAPAN	MALAYSIA	SINGAPORE	SOUTH KOREA	THAILAND	EXPECTED TREND IN COMPETITION
Agriculture / forestry	0.90%	2.40%	16.20%	0.30%	3.60%	6.30%	–	7.10%	**Stable:** modest increases, mostly off-grid
Commercial & public	29.50%	8.00%	8.70%	34.20%	15.10%	24.30%	42.50%	17.60%	**Increase:** linked to cooling, data centres, and electrification
Industry	35.60%	59.70%	40.60%	35.00%	54.20%	32.40%	37.30%	48.30%	**Strong increase**: electrification of heat & processes
Residential	30.90%	17.50%	24.60%	28.50%	21.00%	34.20%	14.40%	24.00%	**Stable:** rooftop PV offsets part of demand
Transport	3.10%	2.60%	2.10%	1.80%	2.00%	0.70%	5.50%	2.30%	**Strong increase:** EVs & charging demand
Other non-specified	–	9.90%	7.80%	0.20%	4.10%	2.10%	0.30%	0.70%	**Increase:** driven by digital & emerging loads (e.g. data centres, AI infrastructure)

Carbon Sources: Competition for CO_2 is limited today but will grow as capture infrastructure scales. In most APAC countries (Australia, Japan, South Korea, Singapore), where capture exists, the majority of CO_2 is currently earmarked for permanent geological storage[97]. China channels over 40 % to enhanced oil recovery (EOR), while India splits volumes between EOR and industrial utilisation. For PtX fuels, this creates both opportunities and challenges: in storage-oriented markets, redirecting a portion of suitable streams to SAF could add value without displacing major uses; in EOR-heavy regions, SAF producers will compete with oil companies for high-purity CO_2 streams. Over time, CCUS developers may prioritise SAF offtake if crediting frameworks make low-carbon fuels more valuable than EOR[95].

Biogenic CO_2 is smaller in scale but often geographically concentrated and relatively low-cost. In India and China, fermentation industries provide several Mt CO_2 per year, whereas Japan, South Korea, and Singapore offer negligible volumes[49,55]. Competing uses are limited (e.g., beverages and chemicals), but logistics and recognition under CORSIA/RED will determine practical supply.

Direct air capture (DAC) could ultimately offer a large, flexible CO_2 pool if deployed at scale, but near-term uptake is constrained by high costs and electricity requirements[95].

Green Hydrogen: Green hydrogen is both a critical feedstock and an intermediate product. In APAC, project pipelines are dominated by Australia, China, and India, while Japan, South Korea, and Singapore remain reliant on imports[65].

Competition is already emerging. Global data on firm offtake agreements between 2020–2024 show that ammonia and refining together account for more than 50 % of committed volumes, followed by shipping and methanol (see **Figure 7**). Aviation represents less than 20 %, highlighting the challenge of securing SAF-dedicated hydrogen[36]. In APAC, ammonia plays a central role in Australia and India through export-oriented projects; methanol dominates in China's chemical sector. Mobility and power compete for flexible volumes but remain secondary. For SAF producers, this means competing against large-scale, long-term industrial contracts. Moreover, Certification frameworks, like CORSIA, EU RED and RSB, increasingly require renewable, additional hydrogen for aviation fuels, which narrows the eligible pool and reinforces the need for dedicated projects and firm offtakes.

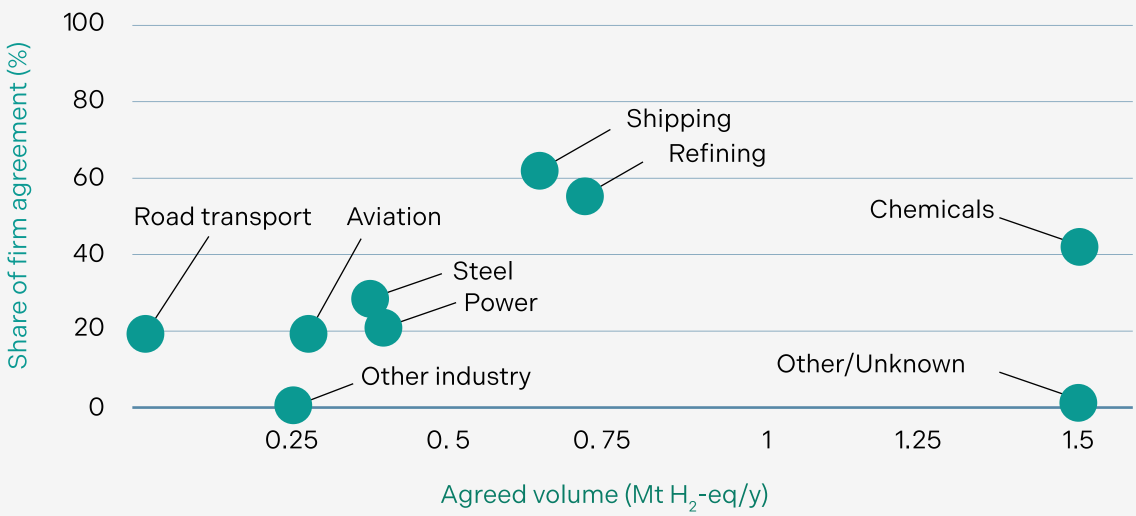


FIGURE 7 **GLOBAL DISTRIBUTION OF FIRM HYDROGEN OFFTAKE AGREEMENTS BY SECTOR, 2020–2024[36]**

Aviation represents a small but growing share, compared to ammonia, refining, and shipping. Figure adopted from IEA's Global Hydrogen Review 2024[36].

Other Resources: Other inputs face more diffuse competition and siting constraints:

- *Biomass residues* already serve energy, feed, and materials; only surplus streams fit sustainability frameworks[8,47].
- *CRMs* (like nickel, cobalt, PGMs) compete with batteries and other clean-energy tech, potentially tightening electrolyser/catalyst supply[34,98].
- *Land* is contested across agriculture, urban growth, forestry, and RE siting, underscoring integrated spatial planning[8].
- *Freshwater competition* is most acute where agriculture dominates withdrawals; seawater is abundant, with desalination limited by costs and local safeguards[43,49].

These dynamics are summarised in **Table 15**. For CO_2, both industrial and biogenic capture streams are included (DAC excluded). For water, only freshwater competition is shown.

Resource and Technology Trading Potentials

The APAC region has clear potential for cross-border trading of PtX fuel resources and enabling technologies. Resource endowments are uneven—e.g., critical raw materials (CRMs) are concentrated in a few countries, and renewable electricity/hydrogen strengths cluster in others—creating natural complementarities (see Section 4.2). Public datasets and institutional reviews likewise highlight China's central role in CRM mining/refining and Australia's strong renewable and hydrogen pipeline growth, while regional policy frameworks will shape the trading rules of the game.

What might trade involve?

- **Biomass and residues.** Countries with large agricultural systems (notably India and Australia) have significant residue potential, while Japan and Singapore face structural constraints and will rely more on imports of sustainable intermediates[82,85].
- **Renewable electricity.** Power itself is rarely traded directly across borders, but under-sea High-Voltage Direct Current (HVDC) concepts and hydrogen derivatives (ammonia, methanol, e-fuels) are under active study as export vectors—especially from Australia to demand centres in Japan and South Korea[65,96,99].
- **Captured CO_2.** Given logistics and regulatory constraints, CO_2 is likely to remain mostly domestic, though China's developing CCUS project pipeline could support limited regional exchanges where transport and storage are in place[97].
- **Green hydrogen.** Expect H_2 and its derivatives to be the most dynamic traded vectors in APAC, with Australia as a large-scale exporter and Japan, South Korea, Singapore—and near-term China—as importers[65,96].

TABLE 15 PRIMARY COMPETING SECTORS FOR PTX FUEL RESOURCES IN APAC

RESOURCE	PRIMARY COMPETING SECTORS
Renewable Energy	Industry > Digital infrastructure (data centers, AI computing) > Commercial/Public Services > Residential > Transport > Agriculture
Captured CO_2	Geological Storage > Enhanced Oil Recovery > Industrial Utilisation > Low-Impact Uses (incl. beverages, urea, chemicals for biogenic streams)
Green Hydrogen	Ammonia > Methanol > Mobility > Power Generation > Other Industries
Critical Raw Materials	Clean-Energy Technologies (batteries, wind) > Industrial Manufacturing (steel, alloys) > High-Tech (graphite, catalysts)
Water (freshwater)	Agriculture > Industry (manufacturing, fuel synthesis) > Municipal > Environmental flows
Land	Agriculture > Urban/Infrastructure > Forestry > Renewable Energy siting
Biomass (residues)	Energy (cogeneration, pellets) > Animal Feed > Materials (board, pulp, paper) > Fertilizer/soil conditioning > Local uses

Resource and technology trading potentials. As illustrated in Section 4.2.4, the APAC resource base is unevenly distributed, creating natural complementarities for cross-border trade in PtX resources and enabling technologies. Public datasets and institutional reviews[96,97,100,101] support this study's findings: China hold strong positions in critical materials, Australia shows major renewable-power and green-hydrogen build-out, and Japan and South Korea exhibit notable technology strengths. Harmonised accounting and certification under relevant schemes, such as EU RED, CORSIA and RSB Global (see Section 5), will shape how these flows scale and are recognised across borders.

Taken together, these findings suggest the following trading roles in APAC (see **Table 16**): Australia emerges as the principal exporter of green hydrogen (via ammonia) and prospective "green electrons" through under-sea HVDC concepts, while China functions as a scale-dominant hub exporting captured CO_2 and critical minerals and importing green hydrogen in the near term. India is an emerging biomass-and-hydrogen player, exporting residue intermediates (e.g., rice-straw briquettes) and low-cost pre-treatment equipment. Japan, South Korea, and Singapore act as technology-led, import-reliant innovators, exporting advanced electrolysers and stack components, hydrogen compression systems, modular biorefinery units, and digital SAF traceability platforms, while importing biomass intermediates and green hydrogen. Because of logistics and regulation, captured CO_2 is likely to remain largely domestic, though China's developing CCUS pipeline could support niche regional exchanges. Renewable electricity itself is rarely traded, but hydrogen derivatives (ammonia, methanol, e-fuels) and selected HVDC links under study provide practical export vectors.

Taken together, these roles suggest *emerging APAC trading corridors*: hydrogen derivatives from Australia to Japan, the Republic of Korea, and Singapore (IEA Electricity 2024; IEA Hydrogen Projects Database); residue intermediates from India to Japan, the Republic of Korea, and Singapore (FAO/World Bank; CSIRO); and CO_2 plus critical minerals from China to regional markets, with China a near-term hydrogen importer (IEA CCUS Projects Database; EC RMIS; USGS *Mineral Commodity Summaries* 2024). In parallel, Japan, the Republic of Korea, and Singapore export electrolyser/components, compression systems, and digital traceability (IEA technology/project databases). With aligned certification (EU RED II/III; RSB; ICAO CORSIA) and bankable offtakes, these corridors can help de-risk early SAF deployment and accelerate APAC's PtX supply.

TABLE 16 INDICATIVE TRADING ROLES, EXPORTS AND IMPORTS OF SELECTED APAC ECONOMIES IN PTX FUEL RESOURCE AND TECHNOLOGY SUPPLY CHAINS

COUNTRY	TRADING ROLE IN APAC	POTENTIAL EXPORTS	POTENTIAL IMPORTS
Japan	Import-reliant innovator and technology leader	Advanced electrolysers and hydrogen compression systems Digital SAF monitoring & traceability platforms	Biomass residue intermediates (e.g., rice-straw briquettes/pellets) from India/Australia Green hydrogen (ammonia) from Australia
South Korea	Tech-focused grower and system integrator	Electrolysis stack components & fuel-cell modules Digital supply-chain / traceability tools	Biomass residue intermediates from India; Green hydrogen (ammonia) from Australia
Singapore	Innovation and logistics hub	Modular biorefinery units & catalyst kits Digital platforms for feedstock traceability	Biomass residue intermediates from India/Australia Green hydrogen (ammonia) from Australia
India	Emerging biomass & hydrogen player	Residue intermediates (e.g., rice-straw briquettes/ pellets) Low-cost biomass pre-treatment equipment	CO_2 capture equipment/services PEM/AEL electrolysers from Japan/South Korea
Australia	High-growth exporter (Hydrogen & minerals)	Green hydrogen via ammonia Prospective "green electrons" via HVDC concepts	Refined graphite/cobalt and other CRM intermediates from China
China	Scale-dominant hub (materials & CO_2 tech)	Critical minerals and refined materials (e.g., nickel/ cobalt intermediates, graphite) CO_2 capture equipment/services	Green hydrogen (ammonia) from Australia

5

SUSTAINABILITY CERTIFICATION FOR PTX FUELS IN APAC

Sustainability certification plays a central role in enabling the uptake of PtX fuels. It provides assurance that fuels deliver real GHG reductions and comply with environmental and social safeguards, while also ensuring recognition under regulatory frameworks and voluntary market mechanisms.

Understanding the certification landscape is critical for policymakers and industry actors in APAC, as compliance requirements and market opportunities differ across certification schemes.

This section focuses on the three most relevant and widely applicable schemes for PtX fuel deployment in APAC (see **Figure 8**):

- **ICAO CORSIA**, as the primary regulatory framework for international aviation;
- **EU RED III**, for producers targeting exports to Europe; and
- **RSB's Global Certification Scheme for Advanced Fuels**, as a voluntary but comprehensive system that bridges gaps in domestic regulation and supports PtX-specific sustainability safeguards.

These schemes are examined in detail to clarify key concepts such as additionality, temporal correlation, and geographic deliverability, and to support credible, scalable certification of PtX fuels in the APAC context.

ICAO CORSIA
REGULATORY, GLOBAL

Compliance with ICAO CORSIA regulations

CORSIA Eligible Fuels information

RSB Standard for ICAO CORSIA

EU RED III
REGULATORY, EUROPERAN UNION

Compliance with EU public policies and market regulation

EU RFNBO information

RSB Standard for RFNBOs and RCFs

RSB GLOBAL CERTIFICATION
VOLUNTARY, GLOBAL

Global scope with broader social and environmental requirements

RSB Global Certification for Advanced Fuels

FIGURE 8 **OVERVIEW OF SUSTAINABILITY CERTIFICATION FRAMEWORKS FOR PTX FUELS COVERED IN THIS STUDY**

5.1 OVERVIEW OF KEY CERTIFICATION FRAMEWORKS

Each of the three certification systems shown in **Figure 8** defines distinct sustainability and GHG performance requirements for PtX fuels. While their detailed provisions on electricity and carbon sourcing are discussed in Sections 5.2 and 5.3, this section summarises their scope, main features, and relevance for APAC producers and policymakers..

ICAO CORSIA – Global regulatory framework for aviation

- **Purpose:** CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation)[102] defines how airlines can claim emission reductions through the use of certified SAF. It forms part of ICAO's global strategy to achieve carbon-neutral growth in international aviation[a].
- **Application to PtX fuels:** The June 2025 update of the CORSIA methodology[46] introduced explicit criteria for electrofuels with high electricity input, requiring verified electricity sourcing (additionality, temporal, and geographic correlation) and harmonised life-cycle accounting.
- **Regional participation:** Most states with significant aviation markets — including Japan, Korea, Singapore, Australia, New Zealand, Thailand, Malaysia, Indonesia, and Vietnam — are already participating in the voluntary phase[103]. India, while above the ICAO activity threshold, has committed to join from 2027, and Vietnam has also announced participation from 2027[104]. China, the region's largest market, currently prioritises domestic mechanisms such as its national ETS and has not confirmed participation in the mandatory phase[105].

a. CORSIA entered a voluntary pilot phase (2021–2026), followed by a mandatory phase from 2027 onward. States representing more than 0.5 % of global aviation activity in 2018 are obliged to participate from 2027, while others may join voluntarily.

- **Certification:** Producers must certify fuels through an ICAO-approved scheme (e.g. RSB CORSIA, ISCC CORSIA) for airlines to claim emission reductions.

EU RED III – Regulatory framework for the EU renewable-fuel market

- **Purpose**: The EU Renewable Energy Directive III (RED III)[10] sets binding sustainability and GHG-reduction criteria for all renewable fuels supplied in the EU.

- **Application to PtX fuels:** RED III defines *Renewable Fuels of Non-Biological Origin (RFNBOs)* — such as e-hydrogen or e-kerosene produced from renewable electricity and captured CO_2 — and Recycled Carbon Fuels (RCFs) derived from waste or residual industrial gases. Both categories can qualify when they meet the required sustainability and emissions-reduction thresholds (≥ 70 % GHG savings vs fossil fuel).

- **Low-carbon hydrogen delegated act:** The European Commission has proposed (not yet adopted) a Delegated Act[106–108] establishing a separate category for hydrogen produced from non-renewable but low-emission sources (e.g. natural gas + CCS or nuclear). The draft requires at least 70 % GHG savings compared with fossil hydrogen (≈ 3.38 kg CO_2-eq/kg H_2). Once approved, it will complement RED III by creating a parallel "low-carbon" category.

- **Regional relevance:** While RED III is designed for the EU market, it serves as a benchmark for APAC PtX fuel producers seeking export access to Europe or alignment with EU sustainability standards. Its definitions and delegated acts on renewable electricity and carbon sourcing have influenced emerging global norms for hydrogen and PtX fuel certification.

- **Certification:** Compliance must be demonstrated via an EU-recognised voluntary scheme such as ISCC EU or RSB EU RED.

RSB Global Certification for Advanced Fuels – Voluntary global standard

- **Purpose:** The RSB operates a comprehensive voluntary certification system for PtX fuels, the RSB Global Certification for Advanced Fuels[39], that covers environmental, social, and climate safeguards beyond regulatory minimums.

- **Application to PtX fuels:** RSB certifies renewable-electricity and carbon sourcing for e-fuels and applies 12 sustainability principles addressing GHG reduction, biodiversity, human rights, and community benefits (see **Figure 4**).

- **Recognition:** RSB certification is accepted under both CORSIA and RED III modules, allowing producers to meet multiple market requirements with one system.

- **Relevance for APAC:** Provides a credible pathway for demonstrating sustainability where national regulations are still evolving, supporting access to both regulatory and voluntary aviation-fuel markets.

At a glance, **Figure 17** summarises the core features and interlinkages of these three certification frameworks.

TABLE 17 COMPARISON OF KEY REQUIREMENTS UNDER CORSIA, EU RED III AND RSB GLOBAL

	ICAO CORSIA	EU RED III	RSB GLOBAL ADVANCED FUELS
Type & scope	Regulatory framework for international aviation.	EU renewable energy deployment directive including renewable fuels in the EU market.	Voluntary global certification system covering advanced and PtX fuels.
Geographical coverage	Global (applies to international flights).	EU; relevant for exporters to the EU.	Global, recognised under CORSIA and RED III.
Eligible fuels	Sustainable Aviation Fuels (SAF), including electrofuels.	Renewable Fuels of Non-Biological Origin (RFNBOs) and Recycled Carbon Fuels (RCFs).	Broad range of advanced, renewable, and PtX fuels.
GHG reduction threshold	≥ 10 % GHG savings vs fossil jet fuel[a].	≥ 70 % GHG savings vs fossil comparator.	≥ 70 % GHG savings vs fossil comparator (aligned with RED III).
Electricity sourcing rules (see Section 5.2)	Electricity must meet CORSIA sustainability criteria (five-pillar approach: sourcing, deliverability, temporal matching, additionality, safeguards).	Renewable electricity as defined in RED III Article 2(1); hourly matching required from 2030[b].	Aligned with RED III, with limited flexibility for traceable EACs[c].
CO_2 source eligibility (see Section 5.3)	Biogenic or atmospheric CO_2. Industrial CO_2 accepted if unavoidable.	Biogenic, unavoidable industrial, or captured CO_2 (LCA verified).	Similar to RED III; broader acceptance for traceable renewable sources.
Relevance for APAC (see Section 5.5)	Essential for airlines and SAF producers targeting international routes.	Critical for exporters to the EU or those aligning with EU standards.	Useful where national systems are not yet in place; can bridge compliance across markets.

APAC Perspective on National Readiness for PtX Certification

National and regional certification systems across APAC provide an important foundation for implementing sustainability certification for PtX fuels. While none currently offer a full PtX-specific framework, several initiatives demonstrate increasing alignment with international systems such as CORSIA, EU RED III, and RSB Global Certification.

- **Australia's Guarantee of Origin (GO) scheme**[109] – Legislated under the *Future Made in Australia Act (2024)*[110], the GO framework certifies renewable electricity and low-emission hydrogen with additionality and temporal/geographic matching requirements. It is explicitly designed for interoperability with international schemes, positioning Australia as a regional frontrunner for PtX certification readiness.
- **India's SAF and bioenergy standards**[111] – The *BIS IS 17081:2019* standard sets technical specifications for Sustainable Aviation Fuel (SAF), while India's Renewable Purchase Obligations and bioenergy programmes establish basic sustainability and

a. From 2025, full life-cycle accounting applies to high-electricity fuels under ICAO rules. Annual matching is accepted until 2029; hourly matching applies from 2030 where systems are in place and becomes mandatory for new plants from 2033.
b. Hourly matching is mandatory from 2030, except in grids with ≥ 90 % renewable share or ≤ 18 g CO_2-eq/MJ (per EU Delegated Regulation (EU) 2023/1184).
c. Energy Attribute Certificates (EACs) accepted under CORSIA; limited under RED III; case-by-case under RSB.

legality principles for biomass. Together, they provide a regulatory base that could evolve toward full PtX sustainability certification.

- **China's aviation and carbon frameworks**[112] – The *Civil Aviation Administration of China (CAAC)* has issued SAF blending standards as part of a broader domestic decarbonisation strategy, while China's national Emissions Trading System (ETS) and biomass policies regulate industrial and bio-based carbon sources. These can serve as entry points for future alignment with CORSIA or RSB methodologies.

Experiences from national biomass sustainability schemes—such as Japan's FIT/FIP, Korea's Renewable Portfolio Standard (RPS), and Southeast Asian commodity standards (e.g. ISPO, MSPO)—also provide precedents for legality verification, traceability, and land-use safeguards. These are directly relevant for ensuring that biogenic CO_2 and biomass feedstocks used in PtX fuel production meet the same environmental and social criteria recognised under international certification.

Drawing on these systems can help APAC policymakers to:

- Leverage existing bioenergy experience to define PtX feedstock sustainability requirements;
- Promote regional consistency by avoiding fragmented national rules; and
- Facilitate market access by aligning with global certification expectations under CORSIA, RED III, and RSB Global Certification.

The key characteristics of selected national frameworks are summarised in **Table 18**, which highlights how existing initiatives in India, China, and Australia support future alignment with international PtX fuel certification systems.

TABLE 18 NATIONAL FRAMEWORKS IN APAC SUPPORTING FUTURE ALIGNMENT WITH INTERNATIONAL PTX FUEL CERTIFICATION SYSTEMS

	INDIA	CHINA	AUSTRALIA
Framework	*BIS IS 17081:2019* – Technical specification for SAF blending; no sustainability criteria yet.	*CAAC Technical Requirements* – Domestic SAF blending standards under aviation decarbonisation plan.	*Guarantee of Origin (GO) Scheme* – Implemented under the Future Made in Australia Act (2024).
GHG threshold	Not specified.	Not specified.	≥ 70 % GHG reduction (aligned with RED III).
Electricity rules	No requirements on renewability, additionality, or temporal matching.	Grid-based electricity assumed; no correlation rules.	Renewable electricity required with additionality, temporal and geographic matching.
CO_2 source eligibility	Basic documentation; no third-party verification.	Industrial CO_2 prioritised; DAC not yet included.	Biogenic, industrial, and DAC sources eligible (aligned with RED III).
Traceability	Needed for airline use and export claims.	Limited traceability; under policy development for export alignment.	Full traceability via REGO, RSB, or ISCC certification pathways.

5.2 ELECTRICITY SUSTAINABILITY AND SOURCING REQUIREMENTS

Electricity is the principal input for PtX fuel production, and its sustainable origin is therefore crucial for the overall GHG performance of the final fuel. Ensuring that the electricity used is genuinely renewable – and correctly certified as such – is a core requirement across all sustainability frameworks.

A central challenge is tracing where the electricity is sourced and confirming that its use does not cause indirect fossil-based emissions or negative impacts on the power grid. All certification schemes address this challenge by defining specific **sourcing arrangements** and **sourcing requirements**:

- **Sourcing arrangements** describe how electricity is supplied – either through a **direct connection** to a renewable power plant or from the **grid** under contractual agreements such as Power Purchase Agreements (PPAs) or, in some cases, Energy Attribute Certificates (EACs)[a].
- **Sourcing requirements** define the conditions under which electricity can be considered renewable. These include **temporal matching** (the electricity must be produced and used within a defined time window), **geographic deliverability** (the electricity must be transportable to the production site), and **additionality** (the renewable capacity must be newly built or repowered to meet additional demand).

Figure 9 illustrates these key concepts and shows how certification schemes operationalise them to ensure electricity sustainability and integrity in PtX fuel production.

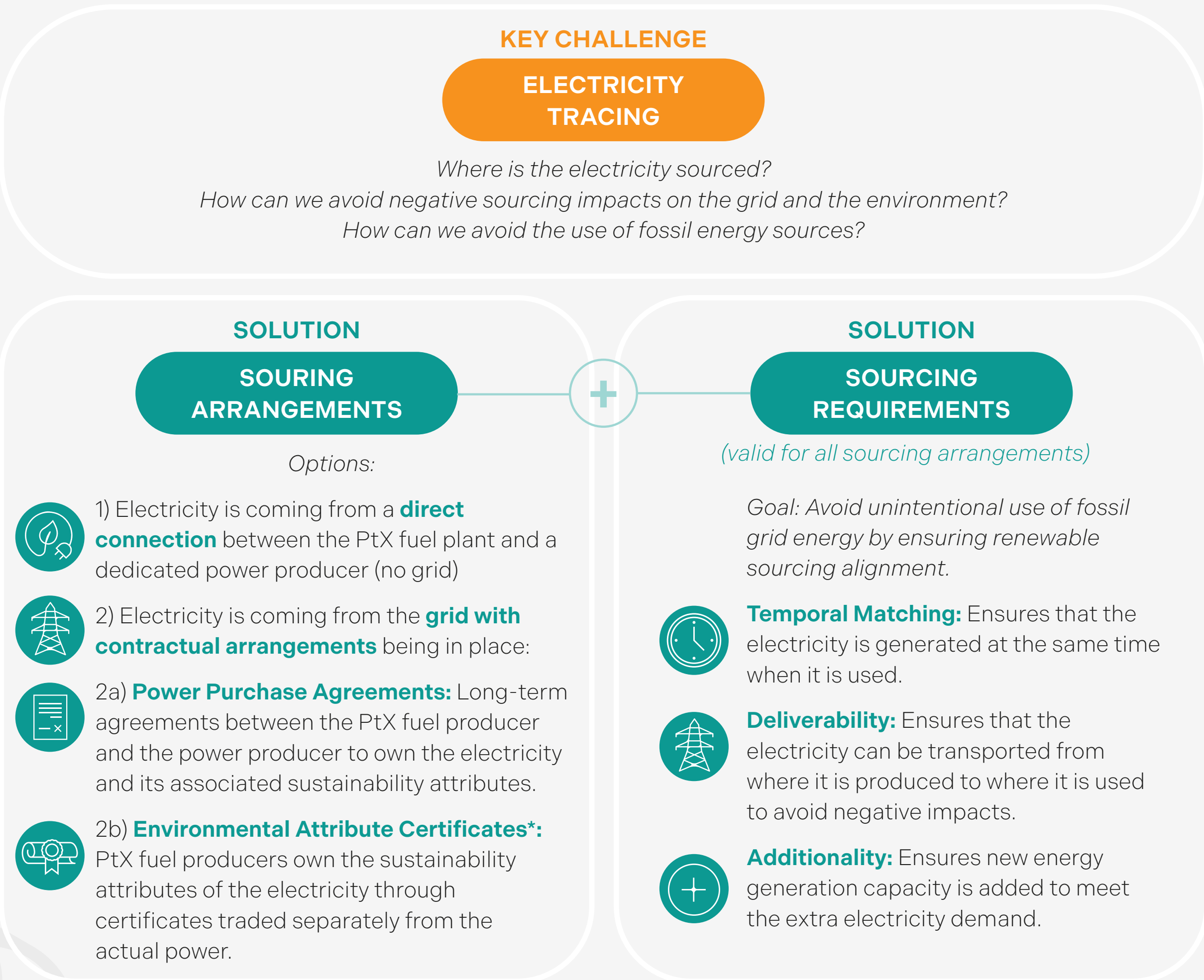


FIGURE 9 ELECTRICITY SOURCING ARRANGEMENTS AND KEY SUSTAINABILITY REQUIREMENTS FOR RENEWABLE ELECTRICITY USED IN PTX FUEL PRODUCTION

a. EACs are recognised under CORSIA but not under EU RED III; they are conditionally accepted under RSB.

5.2.1 Overarching frameworks for electricity sourcing

As illustrated in **Figure 10**, certification systems define two complementary elements to ensure that the electricity used in PtX fuel production is genuinely sustainable and traceable:

(1) **sourcing arrangements**, describing how electricity is supplied to the production site; and

(2) **sourcing requirements**, which set the conditions under which that electricity may be recognised as renewable for certification purposes.

Together, these mechanisms provide the foundation for credible GHG accounting across all frameworks.

Electricity sourcing arrangements

PtX producers may obtain renewable electricity through two main arrangements:

- **Direct connection** – where a renewable power plant (e.g. solar, wind, hydro) is physically connected to the hydrogen or PtX production facility. This arrangement offers the highest traceability but requires co-location or dedicated transmission infrastructure.

- **Grid connection with contractual instruments** – where renewable electricity is delivered via the public grid, accompanied by verifiable contractual evidence such as **Power Purchase Agreements (PPAs), Guarantees of Origin (GOs),** or **Energy Attribute Certificates (EACs)** that link renewable generation to electricity consumption.[a]

These instruments play a crucial role in demonstrating renewable origin and avoiding double counting by proving that an equivalent amount of renewable power has been generated and allocated to PtX fuel production[b].

Electricity sourcing requirements

All three certification frameworks apply three fundamental criteria to determine whether electricity qualifies as renewable for PtX fuel production.

- **Additionality:** Renewable electricity must come from new or recently repowered capacity, typically commissioned within the past 36 months.[c] This ensures that PtX fuel production stimulates additional renewable deployment rather than diverting power from existing consumers, thereby maintaining the environmental integrity of the grid mix.

- **Temporal correlation (see Figure 10a):** Temporal correlation means that electricity generation and PtX fuel production must occur within a defined time window. Initially, monthly or annual matching is accepted, but all schemes are converging toward hourly matching between renewable generation and consumption.[d] Stricter correlation prevents producers from claiming renewable electricity during periods when only fossil-based grid power is available, thus ensuring that PtX fuels genuinely displace fossil energy.

- **Geographical correlation (deliverability) (see Figure 10b)**: Electricity must be generated within the **same grid, market region, or bidding zone** as the PtX fuel production facility.[e] This requirement—sometimes called *deliverability*—ensures that it is physically and commercially possible to transmit the renewable electricity to the point of use and that the same renewable MWh is not claimed by multiple users in different regions.

In summary, certification frameworks apply common overarching rules for renewable electricity sourcing:

- The electricity must come from **new or repowered renewable installations (additionality)**;

- It must be **produced and used within the same timeframe (temporal correlation);** and

- It must be **generated within the same grid or market region (geographical correlation).**

These universal principles underpin the integrity of all PtX certification systems.

Section 5.2.2 describes how these requirements are implemented in practice under CORSIA, EU RED III, and the **RSB Global Certification for Advanced Fuels.**

a. PPAs, GOs, and EACs are contractual or electronic instruments that track renewable electricity from generation to end use. Their recognition and detailed conditions differ across certification frameworks, as discussed in Section 5.2.2.
b. GOs are defined under EU RED III (Art. 19) to prevent double counting; EACs are the international equivalents, including I-RECs and RECs (North America).
c. The "36-month rule" for new or repowered renewable capacity applies in EU RED III and RSB standards and is mirrored in the 2033 CORSIA requirements.
d. CORSIA requires hourly matching from 2030 where systems are in place (mandatory for new plants from 2033); EU RED III requires hourly matching from 2030; RSB is aligned with RED III but allows limited transitional flexibility.
e. Deliverability is defined by grid or bidding-zone boundaries—e.g. EU bidding zones, CORSIA market regions, or national transmission systems.

FIGURE 10a

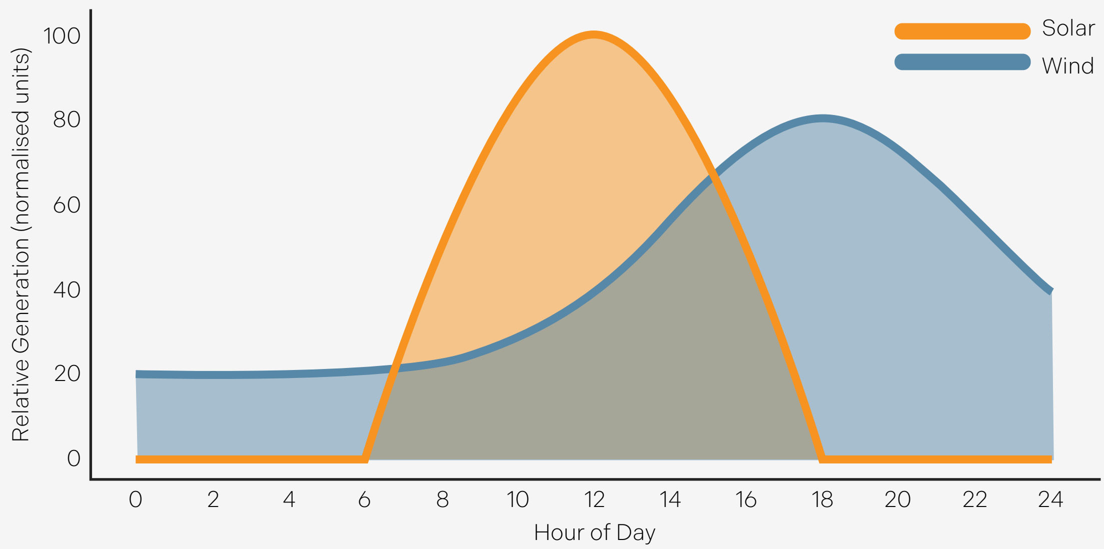


FIGURE 10b

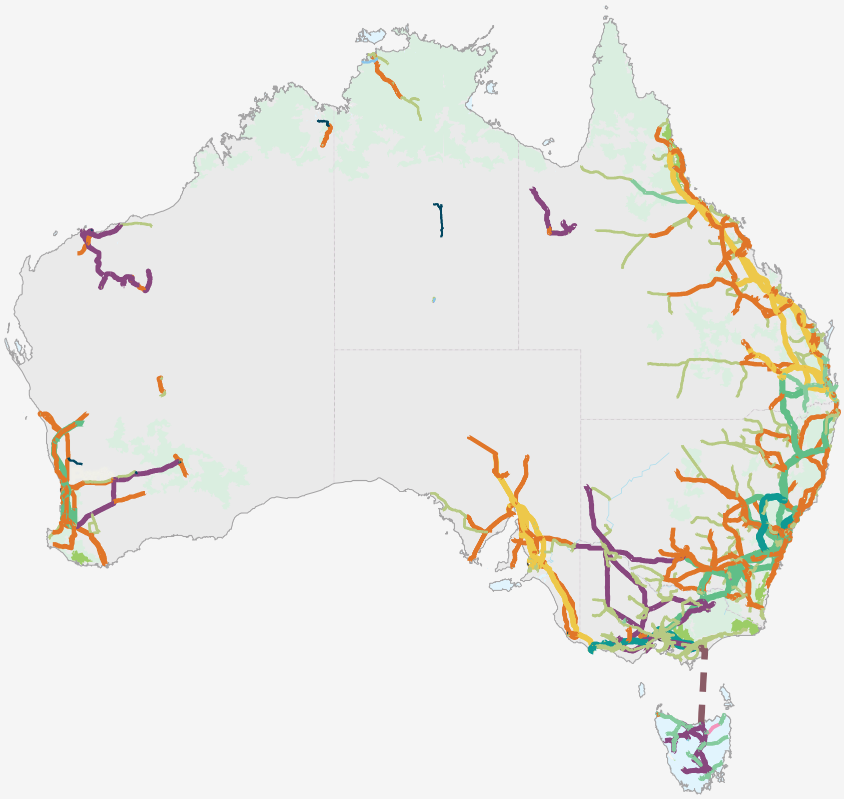


FIGURE 10 **ILLUSTRATIVE EXAMPLES OF ELECTRICITY SOURCING REQUIREMENTS FOR PTX FUELS**

(A) Temporal correlation: Solar and wind generation profiles showing how PtX fuel production must align with renewable electricity availability over time. (B) Geographical correlation: Example of electricity grid zones in Australia, illustrating that renewable power must be sourced within the same connected system as the PtX facility[a].

a. For example, under Australia's National Electricity Market (NEM)[113], renewable electricity generated in Queensland can in principle be delivered to a PtX facility in Victoria, as both lie within the same interconnected grid. In contrast, Western Australia's networks are isolated, meaning cross-grid deliverability does not apply.

5.2.2 Scheme-specific implementations

While all certification systems apply the same overarching electricity sourcing principles — **additionality, temporal correlation, and geographical deliverability** — their implementation timelines, verification methods, and flexibility differ.

These differences influence how PtX fuel producers demonstrate renewable electricity use and achieve compliance under each framework.

Table 19 summarises how these definitions and sourcing requirements are implemented under each framework.

TABLE 19 COMPARISON OF ELECTRICITY SOURCING REQUIREMENTS UNDER CORSIA, RSB AND EU RED III

ASPECT	ICAO CORSIA	EU RED III	RSB GLOBAL
Additionality	Renewable electricity not strictly required, but emissions must be accounted for in the LCA. From 2033, new plants must source ≥ 70 % from direct or contracted renewable sources and ≤ 30 % from traceable EACs, under five pillar rules (sourcing, deliverability, temporal matching, additionality, safeguards). Certain subsidies are allowed.	Renewable electricity as defined in Art. 2(1). Additionality: new or repowered plants ≤ 36 months old, with no subsidies. Renewable power must be new and not double counted.	Renewable, additional, and sustainable electricity required. Recognises PPAs and high-quality EACs if traceable and protected against double counting. New capacity or credible low-impact sourcing must be demonstrated.
Temporal correlation	Annual matching allowed until 2029; hourly matching required from 2030 where systems are in place (mandatory for new plants from 2033).	Monthly matching until 2030; hourly matching mandatory after 2030 (exemptions for ≥ 90 % renewable grids).	Requires monthly temporal alignment between renewable generation and PtX fuel production.
Geographical deliverability	Electricity must originate from the same grid or a directly connected market region, with proof of deliverability.	Electricity must be generated in the same bidding zone as the PtX facility or in interconnected zones under strict conditions.	Electricity must be physically deliverable within the same grid or connected bidding zone.

ICAO CORSIA – Global regulatory framework for aviation

CORSIA defines the electricity sourcing conditions under which airlines can claim verified emission reductions through certified PtX fuels. The June 2025 update[46] introduced detailed requirements for electrofuels with significant electricity input, ensuring renewable electricity integrity through additionality, correlation, and deliverability rules.

- **Definition and scope:** CORSIA does not prescribe a fixed definition of "renewable electricity," but it requires all electricity used in PtX fuel production to be demonstrably low-carbon. In practice, only electricity from renewable sources (solar, wind, hydro, geothermal) or other verifiably low-GHG systems can meet lifecycle reduction thresholds[a].
- **Additionality:** From 2033, at least 70 % of electricity must come from direct or contracted renewable sources, and up to 30 % may be supplied via traceable EACs.
- **Temporal correlation:** Annual matching is accepted until 2029; from 2030 onward, hourly matching applies where monitoring systems are in place and becomes mandatory for new plants from 2033.
- **Geographical deliverability:** Electricity must originate from the same grid or a directly connected region, with evidence of deliverability.
- **Certification and recognition:** Compliance must be verified through ICAO-approved Sustainability Certification Schemes (SCS), such as RSB CORSIA or ISCC CORSIA.

EU RED III – Regulatory framework for renewable fuels in the EU market

RED III defines the most stringent rules for electricity used in PtX fuel production, ensuring high environmental integrity and traceability. It applies uniformly to **Renewable Fuels of Non-Biological Origin (RFNBOs)** and Recycled Carbon Fuels (RCFs). A forthcoming EU Delegated Act on Low-Carbon Hydrogen[106] is expected to further refine correlation and additionality rules, potentially influencing future PtX certification alignment.

- **Definition and scope:** RED III (Art. 2(1) and 2(36)) defines renewable electricity as energy from non-fossil sources such as wind, solar, geothermal, hydropower, and ocean energy. For RFNBOs, only electricity from these non-biomass sources qualifies as renewable input.
- **Additionality:** Renewable plants must be new or repowered within the previous 36 months and operate without public subsidies.
- **Temporal correlation:** Monthly matching is allowed until the end of 2029; from 2030 onward, hourly matching is mandatory (except in grids with ≥90 % renewable share or ≤18 g CO_2eq/MJ).
- **Geographical correlation:** Electricity must be sourced from the same bidding zone or from an interconnected zone that meets strict deliverability criteria. RED III serves as the **benchmark for export-oriented APAC PtX fuel projects**, setting a clear reference for market access to Europe and influencing global definitions of renewable electricity.
- **Certification and recognition:** Compliance is demonstrated via EU-recognised voluntary schemes (e.g. RSB EU RED, ISCC EU) authorised under the RED III framework.

RSB Global Certification for Advanced Fuels – Voluntary global standard

The RSB system provides a flexible yet robust framework for demonstrating renewable electricity use in PtX fuel production, integrating it into broader sustainability criteria.

- **Definition and scope:** RSB recognises electricity from any renewable source, including certified biomass or biogas, provided the feedstock meets its environmental and social sustainability principles. For fuels seeking RED III RFNBO equivalence, only non-biomass electricity may be used.
- **Additionality:** Requires renewable, additional, and sustainably sourced electricity. Recognises **PPAs** and high-quality **EACs**, subject to traceability and anti-double-counting safeguards.
- **Temporal correlation:** Requires at least monthly matching between generation and consumption, moving towards hourly alignment where possible.
- **Geographical deliverability:** Electricity must be physically deliverable within the same grid or interconnected region. The RSB standard is recognised under both CORSIA and RED III modules, allowing producers to meet multiple market requirements through a single certification pathway.

Although the three schemes share the same principles, their specific rules and timelines affect how PtX fuel projects in APAC demonstrate renewable electricity use and plan infrastructure investments. CORSIA offers a practical near-term entry route for aviation fuels, RED III sets the highest regulatory bar for export compliance, and RSB provides a bridge toward global harmonisation.

The next section examines carbon sourcing and sustainability criteria, which complement the electricity requirements outlined above.

a. Until 2029, CORSIA requires that electricity be sourced from facilities not established on converted natural ecosystems (e.g. forests, wetlands, peatlands, mangroves), unless certified otherwise.

5.3 CARBON SOURCING REQUIREMENTS

Beyond electricity, the eligibility of CO_2 sources is a defining element for PtX fuel certification. Certification frameworks differ in how they determine which CO_2 streams qualify for use in PtX fuel production. **Table 20** summarises the key eligibility rules for industrial, biogenic, and atmospheric CO_2 across EU RED III, CORSIA, and the RSB Advanced Fuels Standard.

Under **EU RED III**, eligible CO_2 sources include **biogenic, atmospheric**, and selected **unavoidable industrial point sources**. Industrial CO_2 may qualify only if captured within an effective carbon-pricing system (such as the EU ETS) and used before 2036 — extended to 2041 for non-combustion applications — to avoid lock-in of fossil processes. Deliberately produced CO_2 is excluded.

In the **APAC region**, carbon-pricing systems are gradually expanding. Operational examples include China's national ETS (currently covering the power sector with planned expansion), Korea's multi-sector ETS, and New Zealand's ETS. Singapore and Japan apply carbon taxes, while India is developing a national carbon market under the Energy Conservation (Amendment) Act, with voluntary trading expected by 2025 and mandatory schemes to follow.

Under **CORSIA**, CO_2 from **biogenic, atmospheric**, and unavoidable industrial sources is permitted, provided that it is not deliberately produced and not double-credited elsewhere. Unlike RED III, CORSIA does not require the CO_2 source to be covered by a carbon-pricing mechanism. The updated 2025 methodology further distinguishes between "waste CO_2" and "residue CO_2." Waste CO_2 refers to emissions that the operator intends to discard, while residue CO_2 originates from a process where CO_2 has only an insignificant economic value — typically less than 10 % of the total value of products from that process. Both categories are eligible under CORSIA, reflecting flexibility in recognising unavoidable by-products while preventing deliberate CO_2 generation for fuel production.

The **RSB Global Certification for Advanced Fuels** applies a similar approach but adds broader sustainability safeguards. CO_2 must originate from genuine waste or unavoidable process emissions, and any **biogenic CO_2** must come from feedstocks meeting RSB's environmental and social criteria. RSB also limits recognition of avoided emissions from non-sustainable CO_2 sources beyond 2035.

Direct Air Capture (DAC) is recognised as an eligible source under all three frameworks, provided lifecycle emissions are transparently accounted for.

TABLE 20 ELIGIBILITY OF CO_2 SOURCES UNDER ICAO CORSIA, EU RED III AND RSB GLOBAL

CO_2 SOURCE OR RULE	ICAO CORSIA	EU RED III	RSB GLOBAL
Industrial fossil point-source CO_2	Eligible only if unavoidable waste or residue CO_2, not deliberately produced, and not double-credited.[a]	Eligible for RFNBO/RCF, but avoided-emission crediting allowed only if ETS-priced and used before 2036 (2041 for non-combustion). Deliberately produced CO_2 excluded.	Eligible only if unavoidable by-product, not deliberately produced, and not double-credited.
Biogenic CO_2 from compliant bio-routes	Eligible only if unavoidable by-product, not deliberately produced, and not double-credited.	Eligible only if originating biofuels/bioliquids/biomass fuels meet RED sustainability and GHG criteria, and no prior capture credit claimed.	Eligible only if originating biofuels/bioliquids/biomass fuels meet RSB sustainability and GHG criteria, and no prior capture credit claimed.

a. "Waste CO_2" refers to emissions intended for discard; "residue CO_2" originates from processes where CO_2 has only minor economic value (typically <10 % of total output).

5.4 BIOMASS SOURCING AND BIOGENIC CARBON REQUIREMENTS

Biomass plays a dual role in Power-and-Biomass-to-Liquids (PBtL) and other bio-based PtX pathways—serving both as a primary feedstock and as a source of biogenic CO_2 for fuel synthesis. Its sustainable sourcing therefore determines not only the life-cycle GHG performance of PtX fuels but also their certification eligibility under key frameworks.

Section 3.2.4 provided a detailed overview of biomass resources and residue streams relevant to APAC (see **Table 6**). This section complements that discussion by focusing on how sustainability certification frameworks—EU RED III, ICAO CORSIA, and RSB—define and verify biomass and biogenic carbon requirements.

Across all three schemes, safeguards converge around legality, land use, biodiversity protection, soil and water management, social rights, and traceability, with distinct provisions for residues, wastes, and energy crops. They also link biomass sustainability directly to carbon sourcing: biogenic CO_2 captured from biomass processing or combustion is eligible only when the originating feedstock meets equivalent sustainability and GHG criteria, and no double counting of credits occurs.

- **EU RED III** permits CO_2 captured from certified biofuels, bioliquids, or biomass fuels, provided that all sustainability and GHG thresholds are met.
- **CORSIA** mirrors this approach, allowing biogenic CO_2 from compliant biomass or biofuel systems, subject to the same safeguards and prohibition of double counting.
- **RSB Global Certification** recognises renewable electricity and biogenic CO_2 from certified biomass, provided that the feedstock is certified under RSB or an equivalent scheme, and that CO_2 utilisation does not rely on fossil energy or create lock-in.

Regional experience in the APAC region reinforces these principles. National sustainability schemes and bioenergy policies—such as Japan's FIT/FIP, Korea's RPS, and India's bioenergy programmes—already govern biomass use for power generation and provide a basis for PtX-specific guidance. Abundant residues such as rice straw, palm residues, and forestry by-products offer regionally available, low-carbon feedstocks and eligible sources of biogenic CO_2 when certified under international schemes.

Harmonising biomass and carbon sourcing rules under RED III, CORSIA, and RSB would allow APAC PtX producers to leverage domestic residue resources while ensuring global market eligibility.

Cross-scheme baseline safeguards

Across all three certification frameworks, a common set of sustainability safeguards governs biomass sourcing. These aim to ensure that bio-based PtX pathways contribute to climate goals without undermining environmental or social integrity.

- **No conversion of high-value ecosystems:** All frameworks exclude biomass from land converted from high-biodiversity or high-carbon-stock ecosystems (e.g. forests, peatlands, wetlands, mangroves).
- **Soil protection and residue management:** Operators must demonstrate sustainable residue removal rates, maintain soil fertility, and prevent erosion.
- **Water protection:** Compliance with national water legislation is required under RED III; RSB further requires protection of water rights and downstream users.
- **Social safeguards:** All frameworks include basic labour and land-rights protections; RSB additionally requires Free, Prior, and Informed Consent (FPIC) and equitable community benefits.
- **Legality and traceability:** Proof of legal origin and full chain-of-custody traceability are required. RSB applies independent auditing to prevent double counting.

Biomass feedstock categories and evidence expectations

Certification frameworks classify biomass into several broad categories, each with specific evidence requirements:

- **Agricultural residues (e.g. straw, husks, bagasse):** Demonstrate legality, proof of residue classification, and sustainable removal rates.
- **Forestry residues and by-products:** Show sustainable forest management and conservation compliance, including regeneration and biodiversity safeguards.

- **Biogenic wastes (e.g. MSW biogenic fraction, sewage sludge):** Prove adherence to the waste hierarchy, traceability, and absence of prohibited materials.

- **Dedicated energy crops (where allowed):** Show compliance with land-use, soil, water, and social criteria, and demonstrate that cultivation does not occur on high-biodiversity or high-carbon-stock land.

Key residue streams relevant for APAC—such as rice straw, palm residues, and forestry by-products—are detailed in **Section 3.2.4 and Table 7**.

In summary, residues and wastes represent the most credible biomass inputs for PBtL and other bio-PtX pathways. Certification frameworks converge on common sustainability safeguards while differing in detail and verification depth. Integrating biomass and biogenic carbon sourcing criteria will strengthen regional consistency, reduce certification costs, and support APAC producers in meeting RED III, CORSIA, and RSB requirements simultaneously.

5.5 IMPLICATIONS FOR APAC

The certification requirements for electricity and carbon sourcing under EU RED III, CORSIA, and RSB have significant implications for the development of PtX fuels in the APAC region. Compliance will not only determine export access but also shape how domestic frameworks evolve to ensure credibility and interoperability with global markets.

Electricity sourcing will likely represent the most immediate challenge. In coal-dominated grids such as those of India and Indonesia, PtX producers cannot rely on grid-average electricity to demonstrate compliance with international certification rules. Instead, they will need to secure **dedicated renewable capacity** and, in most cases, integrate **storage systems** to satisfy additionality and temporal correlation requirements. Geographical deliverability rules further restrict the use of distant generation assets or unbundled certificates, allowing only electricity that can be physically transmitted within the same grid or bidding zone.

By contrast, markets with a **high share of renewables**—such as Australia and New Zealand—face fewer structural barriers but must still prove that renewable electricity originates from **new or repowered plants** and that **hourly or monthly matching** between generation and consumption is achieved.

Establishing credible evidence systems for renewable electricity use will be critical. In mature markets with centralised grid operation and digital metering, creating **Guarantee of Origin (GO)** or **PPA** frameworks is relatively straightforward. Across the region, however, readiness varies:

- **PPAs** are well established in liberalised markets such as Australia, Japan, and India, enabling direct renewable contracting, but remain limited in vertically integrated power systems (e.g. much of Southeast Asia).

- **Energy Attribute Certificates (EACs)**, particularly through the International REC (I-REC) system, are now recognised in over 15 APAC countries—including China, India, Indonesia, and Vietnam—and provide traceability where national certification is still absent.

- **Guarantees of Origin (GOs)** are emerging more selectively. Australia legislated its REGO scheme in 2024 to certify renewable inputs and low-emission products, while other markets remain in pilot stages or rely on voluntary mechanisms.

For policymakers, this uneven readiness implies that while renewable procurement evidence is technically feasible across much of APAC, **convergence toward GO-type systems** and **harmonisation of PPA/EAC rules** will be essential to ensure that PtX producers can credibly demonstrate additionality, temporal correlation, and geographical deliverability in line with RED III, CORSIA, and RSB standards.

Biomass and CO_2 sourcing represent a parallel area of opportunity and constraint. APAC countries possess vast residues and wastes—such as rice straw in India, palm residues in Southeast Asia, and forestry by-products in Japan and Korea—that can serve both as feedstocks for Power-and-Biomass-to-Liquids (PBtL) pathways and as sources of biogenic CO_2 for PtX fuel synthesis. However, certification frameworks apply **strict sustainability safeguards**:

- All three schemes—RED III, CORSIA, and RSB—prohibit feedstock from land converted from high-biodiversity or high-carbon-stock ecosystems, and require legality, traceability, and sustainable residue management.

- Unsustainable residue harvesting risks disqualifying the resulting CO_2 from eligibility under biogenic carbon rules.

- Industrial fossil CO_2 use is highly constrained: CORSIA and RSB allow only **unavoidable waste or residue CO_2** that is not deliberately produced or double-credited, while RED III restricts eligibility to sectors covered by effective carbon-pricing systems and applies cut-off dates (2036 for power, 2041 for other industries).

For APAC, this means that **industrial CO_2 use remains viable primarily under CORSIA or RSB**, whereas **access to EU markets** will depend on the establishment of credible national carbon-pricing frameworks and harmonised sustainability verification for biogenic CO_2.

Concrete initiatives are already translating these principles into practice.

- **Australia's Guarantee of Origin (GO)** scheme, legislated under the *Future Made in Australia Act (2024)*, certifies renewable electricity (REGO) and low-emission hydrogen, offering a domestic tool aligned with international standards.

- **International RECs (I-RECs)** are increasingly used by PtX developers in India, Southeast Asia, and China to evidence renewable electricity use, often in combination with PPAs. These instruments are becoming critical for early projects seeking compliance with **CORSIA** and voluntary frameworks such as **RSB Global**.

Overall, aligning domestic systems for renewable electricity tracking, biomass certification, and carbon accounting with international criteria will be pivotal for APAC countries to position themselves as credible suppliers in global PtX fuel markets.

5.6 CERTIFICATION PROCESS IN PRACTICE

Certification of PtX fuels follows a structured and transparent procedure common to both regulatory and voluntary schemes (**Figure 11**).

In practice, a producer first identifies the certification framework relevant to its target market—such as EU RED III, CORSIA, or the RSB Global Standard—and prepares supporting documentation, including life-cycle emissions data, evidence of renewable electricity sourcing, and feedstock traceability records.

An independent audit is then conducted by an accredited certification body to verify compliance with the relevant scheme's criteria, including GHG-reduction thresholds, renewable electricity sourcing requirements, and chain-of-custody systems.

When all requirements are met, the producer receives certification and may issue Proofs of Sustainability (PoS) for each certified fuel batch. These PoS documents accompany the fuel through the supply chain, allowing end-users—such as airlines under CORSIA—to claim verified emission reductions. Periodic surveillance audits and oversight by scheme regulators ensure ongoing compliance and prevent double counting or fraud.

This end-to-end process involves a clearly defined ecosystem of actors, shown schematically in **Figure 15**:

- **Operators** – Fuel producers and suppliers responsible for data collection, sustainability management, and compliance with scheme criteria.

- **Certification bodies** – Independent auditors that verify conformity with sustainability requirements and issue certificates.

- **Accreditation and oversight bodies** – Entities ensuring auditor competence and scheme integrity through surveillance and mutual recognition (e.g. ICAO or European Commission).

- **Scheme owners (e.g. RSB)** – Standard-setting bodies that design and implement standards, manage recognition across jurisdictions, and maintain the chain-of-custody framework linking certified operators.

Together, these institutions ensure transparency and trust throughout the PtX fuel certification process—from renewable input sourcing to verified use in aviation.

1 DEFINE YOUR RSB CERTIFICATION SCOPE

- Define the certification scope
- Select the certification scheme/s applied (EU RED, CORSIA and/or RSB Advanced Fuels)

2 APPLY FOR CERTIFICATION

- Online application
- Select an auditor (certification body) and agree on an audit date
- RSB only 2 weeks public comment period

3 PREPARE FOR AN AUDIT

- Conduct a risk assessment
- Conduct a self-evaluation against applicable requirements
- Develop a sustainability approach
- Develop Chain of Custody procedure
- Perform GHG calculation

4 THE AUDIT

- Desk-based preparation
- On-site evaluation
- Identification of non-conformities, if any
- Time to address non-conformities
- CB certificate issued
- Public audit summary published on RSB website

5 ONGOING

- Annual audits depending on your risk classification

FIGURE 11 RSB CERTIFICATION PROCESS—FROM SCOPE DEFINITION TO ONGOING VERIFICATION

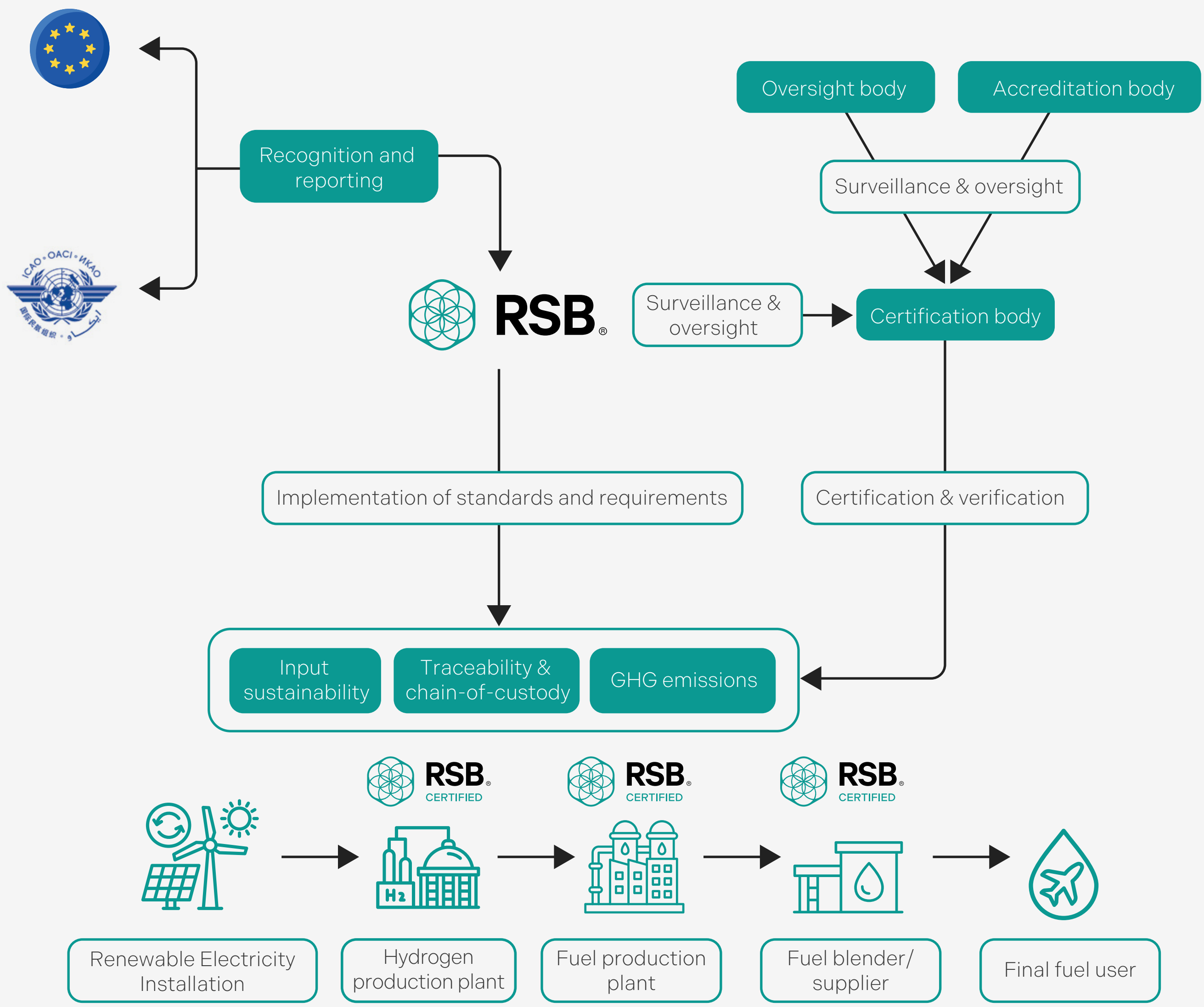


FIGURE 12 **INSTITUTIONAL ARCHITECTURE OF THE CERTIFICATION PROCESS**

To complement **Figures 11** and **12**, **Figure 13** provides an illustrative example of how renewable and sustainable inputs are organised under certification schemes along a **PtL–FT (Power-to-Liquids Fischer–Tropsch)** pathway.

The example shows renewable-electricity sourcing, desalinated water, and biogenic CO_2 feeding electrolysis and FT synthesis, followed by upgrading, blending, and aviation use.

Each stage is certified under the relevant framework (EU RED III/RFNBO, CORSIA, or RSB Global), with chain-of-custody and PoS documentation ensuring that renewable inputs and GHG reductions are fully traceable throughout the supply chain.

After blending PtL SAF may be supplied to airline customers via mass balance supply chains, or allocated to any willing buyer via a dedicated Registry, such as the RSB Book & Claim Registry[a].

a. For more information on SAF book and claim, visit https://rsb.org/programmes/book-and-claim/

Book and Claim for PtX fuels

Book and claim is a system that allows the sustainability benefits of a certified fuel to be transferred without the fuel itself being physically delivered to the buyer. It operates through a secure digital registry where verified 'book and claim units' (BCUs) or 'environmental attribute certificates' (EACs) are issued, transferred between participants, and retired once used.

Book and claim does not require the buyer and the seller to be connected with a physical supply chain, as is the case for other Chain of Custody models such as mass balance. And while a customer may not technically fly or ship their goods on sustainable fuels, their purchase demonstrates market demand and supports the development of supply globally. In turn, they may claim the sustainability benefits, such as the greenhouse gas emission reduction, towards their voluntary targets.

The RSB Book & Claim System – which includes book and claim procedures and a dedicated registry – has been created to monitor and manage this complex but necessary approach to decarbonising the aviation sector.

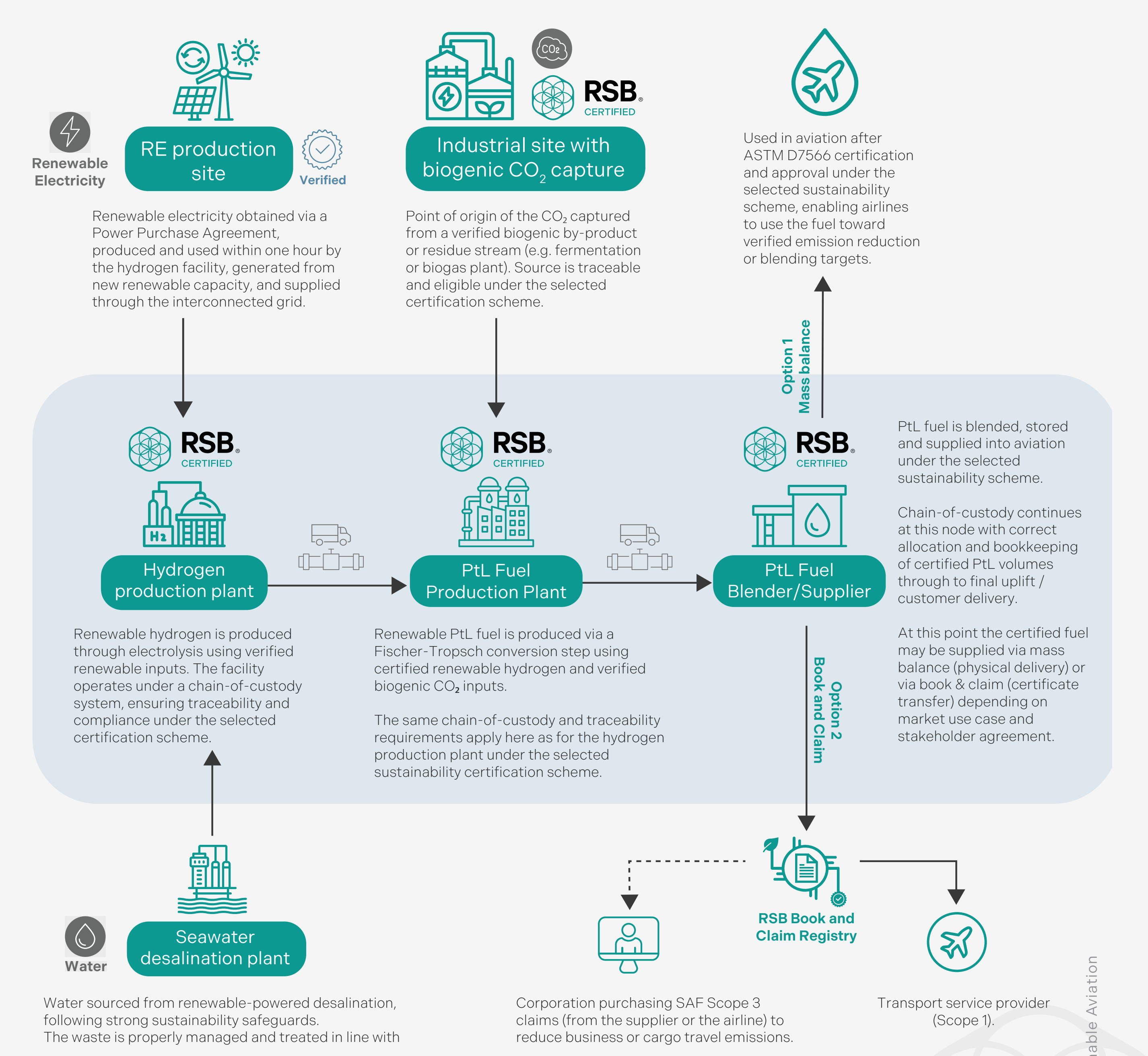


FIGURE 13 **EXAMPLE OF RSB SUSTAINABILITY CERTIFICATION FOR A POTENTIAL PTL-FT PATHWAY**

Example of RSB sustainability certification for a potential PtL-FT pathway, showing certified operators and verified renewable inputs ensuring overall traceability and compliance.

6 PTX SUSTAINABILITY ROADMAP FOR APAC AVIATION

Section 6 brings together the insights from Sections 2–5 and translates them into a forward-looking roadmap for scaling PtX fuels in the APAC region. It identifies the structural enablers that must be strengthened, the critical gaps that risk slowing deployment, and the country-level priorities needed to align policy, investment, and sustainability safeguards. Building on the region's diverse resource base and emerging policy momentum, this section highlights where coordinated action can unlock credible, sustainability-grounded PtX supply chains and support aviation's transition to net-zero. The roadmap provides practical direction for governments, industry, and investors seeking to turn early ambition into measurable, system-level progress.

6.1. KEY GAPS AND SUSTAINABILITY CONSIDERATIONS

Section 6.1 summarises the regional multi-criteria assessment, highlighting the structural, resource, and governance factors that shape each country's readiness for PtX.

Section 6.2 translates these findings into policy, investment, and cooperation pathways for a credible, scalable APAC PtX market. It reflects stakeholder feedback by clarifying criteria weightings, addressing financing and risk allocation, and underscoring the pivotal role of renewable electricity, hydrogen, CO_2 sourcing, and technology supply chains in PtX competitiveness.

6.1.1. Structural Gaps and Enabling Conditions for PtX Fuel Deployment

As outlined in **Section 1**, PtX fuels are a critical—though not yet commercially mature—option for decarbonising aviation in APAC. **PtL** and **PBtL** provide complementary routes to drop-in, high-energy-density fuels. Several configurations are proven at pilot scale, but large-scale deployment depends on more than process efficiency or sustainability performance.

Building on **Sections 2–4**, the main barriers to scaling PtX in APAC arise from persistent **structural gaps** across six interlinked dimensions.

1 **The diversity in policy approaches and progress** remains a core barrier. As outlined in Section 2, SAF blending mandates vary widely across the region: Singapore and South Korea have adopted binding mandates (≈1–5 % by 2030), while Japan's 10 % by 2030 is proposed and not yet binding; Australia, India and China are at voluntary/pilot or developing stages. These disparities, coupled with uneven progress on hydrogen roadmaps and carbon-pricing mechanisms, limit investor confidence and complicate the creation of cross-border supply chains. Addressing these inconsistencies will require more coordinated federal, regional, and national frameworks and clearer administrative responsibilities for SAF and PtX implementation.

2 **Stakeholder imbalances and capacity gaps** mirror these policy differences. Section 2 shows that stakeholder activity—airlines, technology developers, producers, and financiers—remains concentrated in Japan, South Korea, and Singapore, with China emerging as an additional hub. By contrast, initiatives in India and parts of Southeast Asia are still largely government-driven, with more limited private-sector participation. This imbalance could constrain investment mobilisation and slow the development of blending and distribution capacity. In addition, limited technical skills and institutional experience could become a major bottleneck unless targeted capacity-building efforts are scaled up.

3 **Limited technology maturity and infrastructure readiness** persist across the region. While Fischer–Tropsch-based PtL routes are relatively advanced globally, PBtL remains less mature, particularly regarding large-scale biomass and waste gasification. Technical progress is also needed in direct-air-capture (DAC) scale-up, electrolyser efficiency, and flexible operation with variable renewables. Insufficient supporting infrastructure for transporting and storing CO_2 and hydrogen, as well as blending and distribution systems for SAF, remains a challenge. Without these enabling networks, even technically proven processes cannot achieve scale.

4 **Economic and financial constraints** continue to hinder deployment. High capital costs, uncertain and often non-standardised offtake agreements, and competition for renewable electricity and hydrogen across sectors weaken project bankability. Most PtX and SAF projects in APAC remain dependent on equity financing, as the absence of long-term, creditworthy offtake contracts limits access to debt. Strengthening project bankability, for example through the inclusion of long-term environmental attribute certificate off-take agreements with corporations enabled by a book-and-claim mechanism, and greater contract standardisation, will be key to unlocking investment. Dedicated instruments such as Contracts for Difference (CfDs), loan guarantees, concessional finance, and blended-finance facilities are largely absent but will be essential to de-risk early projects and attract private capital at scale.

5 **Sustainability governance across the APAC region is evolving at a different pace.** Although most APAC countries plan to adopt ICAO's CORSIA framework from 2027, implementation approaches differ. Japan, South Korea and Singapore already reference CORSIA in national strategies; India is expected to join at the mandatory stage, while China is developing a domestic scheme. Such divergence introduces uncertainty for producers and may complicate international trade unless further alignment is achieved.

6 **Insufficient renewable-electricity planning** is a systemic gap. As highlighted in Section 4, PtL production will require renewable-power volumes far exceeding current national targets, making electricity availability the first-order constraint on SAF expansion. Even though there are ambitious plans of renewable energy production and investments on the pipeline, countries must integrate aviation-fuel demand into broader renewable-energy planning, considering long-term competition among grid decarbonisation, hydrogen production and PtX fuels. This calls for early, coordinated investment in generation, transmission and storage infrastructure.

Together, these structural gaps, spanning policy, market, technological, financial and sustainability dimensions, define the enabling environment within which PtX fuels in APAC must evolve. They are summarised in **Figure 14** and form the analytical basis for the regional sustainability and readiness assessment that follows.

POLICY FRAGMENTATION

SAF/PtX targets differ widely: Japan 10 %, South Korea 3 %, Singapore 1 %; others at pilot stage.

Misaligned hydrogen and carbon-pricing frameworks hinder cross-border investment.

STAKEHOLDER IMBALANCES & CAPACITY GAPS

Activity concentrated in Japan, South Korea and Singapore; early-stage development elsewhere.

India and China remain government-led with limited private-sector participation and technical expertise.

LIMITED TECHNOLOGY MATURITY & INFRASTRUCTURE READINESS

PBtL gasification, DAC scale-up and electrolyser efficiency remain immature; demonstration scale-up needed.

CO_2/H_2 transport, storage and SAF blending infrastructure underdeveloped.

ECONOMIC & FINANCIAL CONSTRAINTS

High CAPEX, uncertain and short-term offtake agreements, and competition for renewable electricity limit bankability.

De-risking and financing tools (CfDs, guarantees, blended finance, concessional loans) remain scarce across the region.

FRAGMENTED SUSTAINABILITY GOVERNANCE

Most APAC countries plan to adopt CORSIA by 2027, but implementation diverges.

National domestic frameworks may be misaligned with regional and global practices; stronger alignment needed; stronger regional alignment is needed.

INSUFFICIENT RENEWABLE-ELECTRICITY PLANNING

PtL and PBtL expansion will require renewable-power volumes far beyond national targets.

Integrated long-term planning is essential to balance electricity use between grid decarbonisation, hydrogen and PtX fuels.

FIGURE 14 STRUCTURAL GAPS AND ENABLING CONDITIONS FOR PTX FUEL DEPLOYMENT IN THE APAC REGION

6.1.2. Resource Constraints and Sustainability Risk Hotspots in APAC

While Section 6.1.1 outlined the structural gaps constraining PtX-fuel deployment, an equally important consideration is whether these pathways can scale sustainably. The long-term feasibility of PtL and PBtL depends on managing a limited set of critical resources, electricity, water, carbon, biomass residues, land, and critical raw materials, each carrying environmental, social, and economic implications.

Renewable electricity remains the primary constraint. Most APAC countries face trade-offs between decarbonising their power grids and allocating new renewable capacity for hydrogen and PtL production. Addressing these trade-offs requires coordinated planning to expand renewable generation, ensure temporal correlation, and prevent indirect emissions from fossil backup generation.

Building on the detailed resource and sustainability assessments in Sections 3 and 4, this section summarises where resource needs and sustainability risks converge. The magnitude of each constraint reflects both the intensity of demand and the severity of associated environmental or social impacts.

Table 21 provides .a summary of the relative availability of key PtX resources and their associated environmental and social sustainability risks. It also highlights where scarcity and sustainability pressures most contrain large-scale deployment. This review is based on analyses from Sections 3 and 4.

TABLE 21 RESOURCE CONSTRAINTS AND SUSTAINABILITY RISK HOTSPOTS IN THE APAC REGION

RESOURCE	RELATIVE SUPPLY-DEMAND BALANCE	KEY ENVIRONMENTAL & SOCIAL RISKS	IMPLICATION FOR PTX SCALE-UP
Renewable Electricity	**Severe regional shortfall** without major new capacity. Highest potential in Australia, China, and India; limited land and grid capacity in Japan, Korea, Singapore.	**Environmental:** land footprint, biodiversity loss from large solar/wind sites, CRM extraction and waste; need for additional and temporally correlated renewables to avoid indirect emissions. **Social:** land-tenure conflicts, weak FPIC, limited community participation, uneven benefit-sharing.	**Systemic bottleneck:** primary constraint determining feasible PtX scale; requires massive renewable expansion and inclusive planning.
Freshwater	**Moderate-to-high stress** in India, northern China, Singapore; adequate in Australia and parts of Southeast Asia.	**Environmental:** over-abstraction, pollution, ecosystem degradation. **Social:** equity-of-access challenges, competition between industrial and household needs.	**Localised high risk:** critical constraint for inland electrolysis and biomass processing; requires site-specific management.
Seawater (Desalination)	**High potential** along APAC coasts; infrastructure concentrated in China and Australia, emerging elsewhere.	**Environmental:** brine discharge, salinity changes, marine-ecosystem impacts; energy-intensive if non-renewable. **Social:** coastal-community and fisheries impacts if poorly managed.	**Low-to-moderate risk / high potential:** viable mitigation pathway for water-stressed regions when powered by renewables.

Carbon (CO_2)	**Industrial sources abundant** in China & India; **biogenic CO_2 limited;** DAC pre-commercial but essential for long-term scalability.	*Environmental:* fossil lock-in if process CO_2 persists; high energy and water use for DAC. *Social:* traceability and transparency concerns, public scepticism over fossil CO_2 use.	**Transition risk:** industrial CO_2 viable short term; biogenic CO_2 and DAC fundamental for long-term sustainability and credibility.
Biomass Feedstocks (residues & wastes)	**Regionally abundant** yet logistically fragmented; strongest in India, China, Indonesia, Thailand.	*Environmental:* over-harvesting, nutrient depletion, biodiversity loss, methane from unmanaged residues. *Social:* livelihood and food-security implications for smallholders, labour-rights gaps in plantations.	**Selective opportunity:** PBtL viable in residue-rich areas; sustainability hinges on supply-chain control and social safeguards.
Critical Raw Materials (CRMs)	**Supply highly concentrated** in China & Australia; import dependence elsewhere.	*Environmental:* mining emissions, tailings, water contamination, biodiversity loss. *Social:* human-rights and labour-condition risks in supply chains; uneven benefit distribution.	**Medium-term enabling risk:** exposure to supply disruption and ESG concerns; calls for diversification and responsible sourcing.
Land (cross-cutting)	**Limited in dense economies**; contested in parts of South & Southeast Asia; ample in Australia.	*Environmental:* indirect land-use change (ILUC), habitat conversion, biodiversity pressures. *Social:* insecure tenure, weak FPIC enforcement, inequitable compensation.	**Cross-sectoral constraint :** affects renewable siting and biomass expansion; demands integrated spatial planning and social inclusion.

6.1.3. Multicriteria Country-Level Assessment

This section provides a high-level, indicative overview of the enabling conditions for PtX fuel development across APAC. It synthesises the **structural gaps** identified in Section 6.1.1 and the **resource constraints and sustainability risks** discussed in Section 6.1.2 into a unified multicriteria screening. The objective is not to produce exact rankings but to highlight **relative strengths, weaknesses, and complementarities** among countries.

Ten criteria were selected to capture both enabling conditions and resource fundamentals, drawing directly from the detailed analyses in **Sections 2–4**. Each country is qualitatively assessed for its overall favourability toward PtX fuel deployment:

- **Structural criteria** – policy frameworks, stakeholder and industrial ecosystems, enabling and financing conditions, and sustainability governance (measured through CORSIA participation; see Section 2).
- **Resource criteria** – renewable electricity capacity and system readiness (see Section 4.3.1), together with the availability of CO_2, water, biomass residues, and critical raw materials (CRMs) relevant for electrolyser, catalyst, and synthesis-system manufacturing (see Section 4.3.3).
- **Country-level criterion** – an integrated sustainability risk assessment reflecting country-specific environmental and social vulnerabilities, based on the indicators discussed in Section 3.1.

Table 22 summarises the results of this multicriteria screening, based on cumulated findings of this study. It should be interpreted as a structured snapshot rather than a deterministic ranking, illustrating how different enabling and resource factors shape each country's PtX readiness and highlighting where targeted cooperation or investment could address remaining bottlenecks.

TABLE 22 **INDICATIVE MULTICRITERIA SCREENING OF PTX FUEL ENABLING CONDITIONS AND RESOURCE READINESS IN SELECTED APAC COUNTRIES**

	STRUCTURAL CRITERIA				RESOURCE CRITERIA					COUNTRY CRITERIA	
	POLICY	STAKEHOLDERS/ INITIATIVES	ENABLING CONDITIONS	CORSIA PARTICIPATION	RENEWABLE ELECTRICITY CAPACITY	WATER SOURCES	CO_2 SOURCES	BIOMASS AVAILABILITY	RAW MATERIALS	SUSTAINABILITY RISK	TOTAL SCORE
Australia	Moderate	Good	Good	Very good	Good	Very good	Good	Good	Good	Good	Good
China	Challenging	Moderate	Good	Very Challenging	Very good	Moderate	Very good	Very good	Very good	Moderate	Good
India	Moderate	Moderate	Moderate	Challenging	Good	Challenging	Good	Very good	Moderate	Challenging	Moderate
Japan	Good	Good	Good	Very good	Moderate	Moderate	Challenging	Challenging	Moderate	Very good	Good
Malaysia	Moderate	Moderate	Moderate	Very good	Challenging	Good	Good	Good	Challenging	Good	Moderate
Singapore	Good	Good	Good	Very good	Very Challenging	Moderate	Very Challenging	Very Challenging	Very Challenging	Very good	Moderate
South Korea	Good	Good	Good	Very good	Challenging	Challenging	Challenging	Challenging	Moderate	Very good	Moderate
Thailand	Challenging	Challenging	Moderate	Very good	Moderate	Good	Good	Very good	Very Challenging	Moderate	Moderate

Scale indicating conditions for PtX-Fuels: Very good, Good, Moderate, Challenging, Very Challenging

The screening highlights a **highly heterogeneous but complementary landscape** across the region. No APAC country displays uniformly favourable conditions, but several show clear leadership in specific areas:

- **Australia, China, and Japan** emerge with overall **good enabling conditions** for PtX fuel deployment.
  - *Australia* combines exceptional renewable and CO_2 resource potential with a robust policy framework and active stakeholder base, positioning it as a leading large-scale producer and potential exporter.
  - *China* benefits from vast renewable resources, industrial CO_2 availability, and dominance in critical raw material supply chains, underpinning strong domestic production potential. However, sustainability governance and certification

alignment remain areas for improvement.

- *Japan* compensates for its limited domestic resources through strong policy direction, industrial coordination, and CORSIA alignment, establishing it as a frontrunner in technology development, demonstration, and certification frameworks.

- **India, South Korea, Malaysia, Thailand, and Singapore** are assessed as **moderate**, each reflecting distinct strengths and constraints.
  - *India* has substantial renewable and biomass potential but faces challenges related to water stress, land use, and policy consistency. In residue-rich regions, PBtL (hybrid PtX–biomass) could convert agricultural wastes into low-carbon synthetic fuels when coupled with renewable electricity and hydrogen supply.
  - *South Korea* maintains strong industrial and policy capabilities but limited renewable and feedstock availability, making it more reliant on imports.
  - *Malaysia* and *Thailand* show promising biomass and CO_2 potential but slower renewable expansion and limited financing mechanisms, requiring clearer policy signals and stronger sustainability safeguards. Both could pilot PBtL based on palm/forestry residues (Malaysia) and rice/sugar residues (Thailand) if paired with renewable hydrogen and robust sustainability safeguards.
  - *Singapore* combines strong institutional frameworks, CORSIA participation, and stakeholder engagement, but remains highly constrained in domestic resources, positioning it primarily as a regional trading, certification, and finance hub.

Overall, the multicriteria screening confirms that **no single country in APAC can independently cover all critical dimensions for PtX fuel scale-up**.

- **Australia and China** are best placed to serve as major production and export bases.
- **Japan, South Korea, and Singapore** are likely to act as innovation, technology, and governance hubs.
- **India, Malaysia, and Thailand** represent emerging supply bases with strong resource potential but greater sustainability and investment challenges.

This diversity underscores the importance of regional coordination and cross-border cooperation. Shared infrastructure, aligned certification frameworks, and complementary policy strategies can help the region leverage its collective strengths and accelerate the transition toward sustainable PtX fuel deployment.

6.2. PTX AND SUSTAINABLE AVIATION: THE ROADMAP FOR APAC

Building on the structural gaps and sustainability challenges identified in Section 6.1, this section shifts from analysis to action. It outlines regional priorities and country-specific directions that can support the scale-up of PtX fuels in APAC. The aim is not to prescribe detailed national roadmaps but to provide a high-level guide for policymakers, industry, and other stakeholders. The focus is on identifying cross-cutting priorities that apply across APAC while also recognising the differentiated needs and opportunities of individual countries and clusters.

6.2.1. Top 5 Overarching Regional Recommendations

The deployment of PtX fuels in APAC will require coordinated progress across several interconnected fronts. Building on the structural and sustainability gaps identified in Sections 6.1.1–6.1.3, **five overarching priorities stand out where collective regional action could deliver the greatest impact.** They reflect both policy-making and market-integration needs and provide direction for governments, industry, and financial actors.

1 **Strengthen sustainability governance and knowledge exchange:** Sustainability standards remain uneven across APAC. Environmental safeguards for electricity, water, and biomass are comparatively mature, but social safeguards—covering land rights, equity, and livelihoods—lag behind. Continuous improvement through joint research, data sharing, and best-practice learning is essential. Regional dialogue should also expand to emerging issues such as desalination impacts and raw-material sourcing. Building shared understanding among governments, industry, and civil society will enhance the credibility and market acceptance of PtX fuels.

2 **Align and mutually recognise certification systems:** Most APAC countries are aligning with ICAO's CORSIA, yet divergence persists: China is developing a national framework and India remains at the pilot stage. Without interoperability, cross-border trade in sustainable fuels will face high transaction costs. Early dialogue toward mutual recognition between national schemes and international systems (ICAO CORSIA, EU RED III, RSB Global Certification) can enable an integrated regional market. Establishing accredited regional certification bodies or joint verification platforms would further support policy consistency and investor confidence.

3 **Enable regional infrastructure and trade corridors:** Scaling PtX supply chains requires shared logistics for CO_2, hydrogen, biomass, and SAF blending. Coordinated infrastructure planning—such as Indonesia–Singapore biomass-to-liquids corridors, hydrogen and ammonia hubs linking Australia and North-East Asia, or CO_2 transport networks between industrial clusters—can lower costs and balance geographic asymmetries. Harmonised regulations, customs procedures, and carbon accounting frameworks will be crucial to transform these technical links into functioning regional markets.

4 **Foster technology cooperation and market integration:** The multicriteria screening (Section 6.1.3) highlights clear complementarity: Japan, Korea, and Singapore as technology and governance leaders; Australia and China as resource anchors; and India, Malaysia, and Thailand as emerging supply bases. Structured technology-transfer partnerships and joint demonstration projects can accelerate commercial readiness. Integrating PtX into wider energy-market reforms—such as carbon-pricing, hydrogen-trading, and renewable-power-certification systems—will allow market signals to guide investment more efficiently.

5 **Mobilise finance and risk-sharing mechanisms:** PtX fuels in APAC remain several times more expensive than fossil jet fuel. Targeted financial innovation is needed to bridge this cost gap. Instruments such as long-term environmental attribute certificate off-take agreements with corporations enabled by book and claim mechanism to improve project bankability (e.g. RSB Book & Claim System's Market Acceleration Indicator), contracts for Difference (CfDs), concessional loans, green bonds, and blended-finance platforms can de-risk early projects. Coordination among multilateral development banks, export-credit agencies, and regional green-finance facilities would help align incentives, reduce perceived risks, and crowd in private capital for enabling infrastructure.

These five priority areas are interdependent: robust governance and certification underpin trade integration; technology cooperation and finance mechanisms convert potential into practice.

Table 23 summarises indicative short- and long-term measures corresponding to each priority, offering non-prescriptive pathways for coordinated regional action.

TABLE 23 INDICATIVE SHORT- AND LONG-TERM MEASURES FOR PTX FUELS IN APAC

	PRIORITY AREA	SHORT-TERM FOCUS (NEXT 5–10 YEARS)	LONG-TERM FOCUS (POST-2035)
1	**Strengthen sustainability governance and knowledge exchange**	Build capacity among governments, industry, and civil society on evolving sustainability and certification standards (ICAO CORSIA, EU RED III, RSB Global Certification). Conduct regional studies on emerging sustainability topics (e.g. desalination impacts, CRM sourcing, land-use safeguards). Establish regional knowledge networks and technical-assistance platforms for data, LCA methodologies, and MRV systems.	Institutionalise dynamic regional governance platforms to continuously update and align sustainability standards Integrate environmental and social safeguards into national regulations and regional trade agreements. Create permanent regional observatories for sustainability performance tracking.
2	**Align and mutually recognise certification systems**	Support pilot projects to test CORSIA-aligned SAF certification in emerging producers (e.g. India, Malaysia, Thailand). Launch structured dialogue between China's domestic framework and international systems to identify areas for interoperability. Develop regional databases and tracking tools for renewable-power, CO_2, and biomass attributes.	Establish mutual-recognition mechanisms between APAC certification systems and EU/US import standards. Create a harmonised regional certification backbone (e.g. jointly accredited auditors, traceability registries). Converge toward a single APAC sustainability verification protocol for SAF and PtX fuels.
3	**Enable regional infrastructure and trade corridors**	Identify priority cross-border infrastructure opportunities (e.g. biomass-to-liquids corridors Indonesia–Singapore; CO_2 transport networks China–Korea–Japan; hydrogen/ammonia shipping Australia–Northeast Asia). Conduct coordinated feasibility studies and develop enabling regulations for cross-border transport, customs, and carbon accounting. Pilot shared logistics or hub-and-spoke models to reduce transaction costs.	Scale up fully integrated regional PtX supply chains connecting resource-rich and technology-intensive economies. Operationalise APAC-wide SAF trade corridors with common MRV and sustainability assurance systems. Integrate PtX trade into broader energy-market frameworks (e.g. hydrogen-trading hubs, renewable-certificate markets).
4	**Foster technology cooperation and market integration**	Launch bilateral demonstration projects combining complementary strengths (e.g. Australian resources with Japanese/Korean technology). Establish regional R&D funds and innovation challenges on electrolysis, CO_2 capture, and synthetic-fuel production. Integrate PtX fuels into national hydrogen and carbon-pricing strategies to create early market pull.	Institutionalise long-term cooperation via regional R&D centres and innovation clusters. Promote harmonised market instruments (e.g. tradable SAF credits, guarantees of origin). Embed PtX fuels within regional energy-security and decarbonisation strategies.

5	**Mobilise finance and risk-sharing mechanisms**	Identify partnerships for long-term environmental attribute offtakes using book and claim to increase project bankability (e.g. utilising RSB's Book and Claim Market Acceleration Indicator) Expand blended-finance, green-bond, and multilateral guarantee schemes to reduce project risk. Channel early capital into enabling infrastructure (renewables, CO_2 transport, hydrogen hubs, biomass supply chains). Engage regional development banks (e.g. ADB, AIIB) to co-finance first-of-a-kind projects.	Develop long-term investment frameworks that internalise carbon costs and stabilise PtX markets (e.g. CfDs, carbon contracts). Establish APAC-wide green-finance facilities linking private and public capital. Integrate PtX finance within sustainable-aviation and industrial-decarbonisation portfolios.

Taken together, these five priority areas form a practical roadmap for coordinated regional action. They show that scaling PtX fuels in APAC will depend less on isolated national progress than on cross-border cooperation—aligning policy frameworks, certification systems, infrastructure, and financing mechanisms. The next section (6.2.2) translates these enabling dimensions into a spatial perspective, identifying where conditions in the region are most conducive for early PtL and PBtL deployment. It highlights emerging "best spots" for production and trade integration, where resource availability, governance capacity, and infrastructure readiness intersect most favorably.

6.2.2. Regional Roles and Pathways for PtX Scale-up in APAC

Building on the multicriteria screening in Section 6.1 and the trading-potential analysis in Section 4.4.2, this section identifies where PtX fuel production and trade could develop most effectively across the APAC region. Rather than prescribing country-specific targets, it highlights relative strengths and strategic complementarities that can shape regional cooperation and investment priorities.

A differentiated regional landscape

The assessment confirms that APAC's PtX readiness is highly uneven. No single country combines all the required elements, renewable power, CO_2 sources, feedstock supply, industrial capacity, and governance alignment, but taken together, their strengths are complementary:

- **Australia** emerges as the most favourable overall environment for large-scale PtL and hydrogen-derived fuel production. It combines abundant renewable-electricity potential, strong policy support, and growing infrastructure for hydrogen and ammonia exports. The country's challenge remains the remoteness of sites and the need to scale enabling infrastructure (CO_2 transport, desalination, and storage).

  Role: regional *energy* and *PtX exporter*.

- **China** is the *industrial powerhouse* of the region, with dominant refining capacity for critical raw materials, extensive CO_2 point sources, and advanced electrolyser manufacturing. While its renewable share still lags behind its total demand, China's ability to scale rapidly positions it as a *technology and volume leader.* Long-term sustainability and certification alignment will determine its international integration.

  Role: technology and volume leader

- **Japan** and **South Korea** are *technology and governance leaders*. Both have ambitious policy frameworks, strong industrial ecosystems, and full CORSIA alignment but limited domestic resources. Their roles will focus on technology export, certification development, and stable offtake markets for imported PtX fuels—especially from Australia and emerging Southeast Asian suppliers.

  Role: technology and governance leaders

- **India** combines vast biomass residue potential with a fast-growing renewable-energy sector, positioning it as a *PBtL leader* and a future hydrogen producer. However, water stress, fragmented logistics, and uneven policy coordination will require capacity-building and sustainability safeguards.

  Role: PBtL leader and future hydrogen produce

- **Singapore** stands out as a *regional finance, certification, and trading hub*. With limited domestic resources, its comparative advantage lies in logistics, verification platforms, and regional market integration. Singapore can anchor the development of APAC-wide SAF and PtX value-chain transparency systems.

  Role: regional finance, certification and trading hub

- **Malaysia, Thailand,** and **Indonesia** represent emerging Southeast Asian clusters with high potential for PBtL pathways.
  - Malaysia combines good renewable and water availability with moderate industrial CO_2 and growing palm-residue resources; it can play a bridging role in regional biomass-to-liquids trade.
  - Thailand shows solid agricultural-residue potential and improving renewable readiness, suggesting opportunities for hybrid PtL/PBtL demonstration projects.
  - Indonesia's biomass abundance and emerging hydrogen export ambitions make it a promising partner for cross-border projects—particularly with Singapore and Japan—though sustainability and governance safeguards are critical to avoid deforestation and land-use conflicts.

"Best spots" for PtX production

Drawing on these complementary advantages, several *prospective hotspots* for PtX deployment can be identified:

1. **Australia's coastal renewable-hydrogen** clusters (Pilbara, Gladstone) – best suited for PtL exports due to renewable abundance, existing port infrastructure, and export-market alignment.
2. **India's western and southern regions** (Gujarat, Tamil Nadu) – favourable for PBtL (hybrid PtX-biomass) projects leveraging biomass residues and renewable expansion.
3. **China's eastern industrial corridor** – conducive for large-scale CO_2 capture and technology manufacturing.
4. **Indonesia–Malaysia biomass corridor** – high PBtL potential from palm and forestry residues, conditional on sustainability certification.
5. **Singapore–Japan–South Korea triangle** – central to market integration, technology development, and certification alignment.

Figure 15 provides a synthesis of regional readiness and resource endowments for PtX fuel development. It plots key APAC economies along two axes, policy and market readiness (vertical) and resource and feedstock potential (horizontal), while bubble size indicates the indicative PtX scaling opportunity based on combined policy, infrastructure, and resource criteria.

Distinct clusters can be observed: large-scale resource exporters (e.g. Australia), advanced technology and trading hubs (Japan, Korea, Singapore), and emerging production hubs (China, India, and Southeast Asia). The positions reflect cumulative findings across Sections 4 and 6, illustrating how readiness and resource endowment interact to define each country's likely PtX role in the regional ecosystem.

Building on the spatial screening of emerging PtX "hot spots" across APAC, **Table 24** summarises the indicative country roles and comparative strengths identified in this study. It integrates the findings from Sections 2–4 and the multicriteria screening in Section 6.1.3, highlighting where complementary advantages exist across resources, technology readiness, and governance capacity. Rather than assigning rigid categories, the table illustrates how differentiated roles, ranging from large-scale producers to innovation and trading hubs, could jointly underpin a regionally integrated PtX ecosystem.

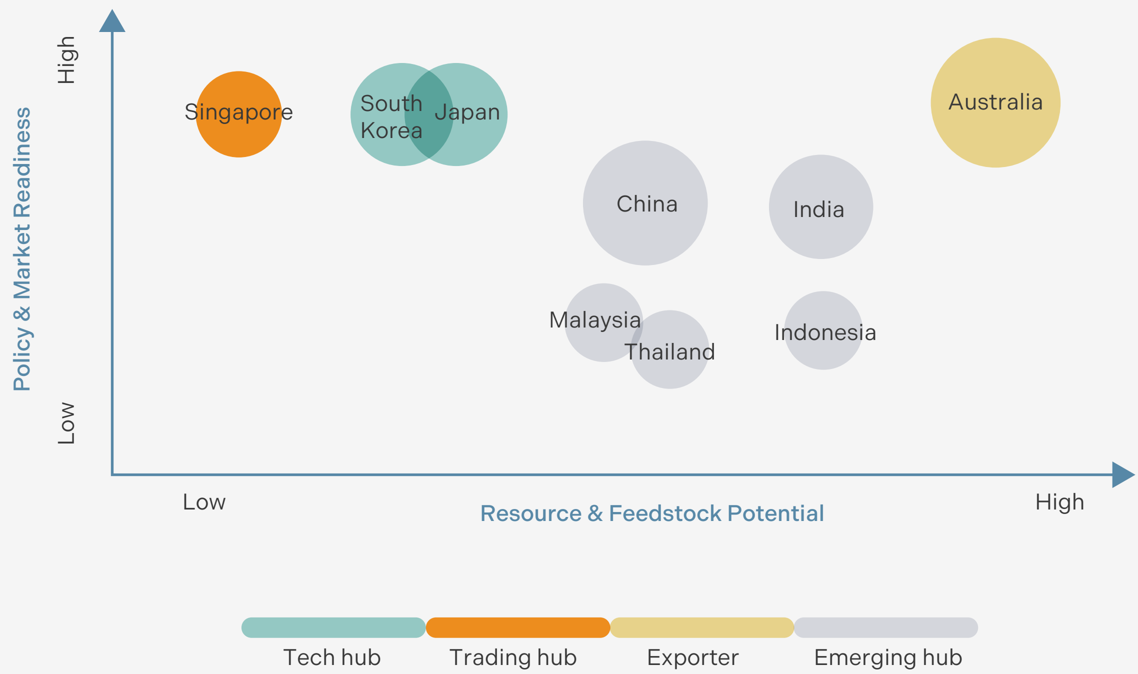


FIGURE 15 **INDICATIVE PTX FUEL READINESS, RESOURCE POTENTIAL, AND SCALING OPPORTUNITY ACROSS APAC**

Indicative PtX fuel readiness, resource potential, and scaling opportunity across APAC (bubble size = indicative scaling potential). Countries occupy distinct roles in the regional PtX fuel ecosystem: Australia leads as a large-scale exporter; Japan, Korea, and Singapore act as technology and trading hubs; and emerging hubs such as China, India, and Southeast Asia bridge resource potential with growing policy readiness.

Toward coordinated regional scaling

Together, these patterns suggest that APAC's PtX ecosystem will evolve through *specialised national roles linked by regional trade corridors,* not a single integrated market. Harmonised certification, infrastructure connectivity, and coordinated financing (Sections 6.2.1 and 6.1.1) will be prerequisites for achieving economies of scale.

Regional cooperation, anchored in early bilateral initiatives and supported by platforms such as ASEAN, APEC, and ICAO, can transform these differentiated strengths into a coherent APAC PtX network, capable of supplying a significant share of global sustainable-aviation-fuel demand by 2050.

TABLE 24 INDICATIVE COUNTRY ROLES AND PTX FUEL OPPORTUNITIES IN THE APAC REGION

	INDICATIVE ROLE IN REGIONAL PTX ECOSYSTEM	KEY STRENGTHS	MAIN CHALLENGES / CONSTRAINTS	MOST SUITABLE PTX PATHWAYS
Australia	Renewable- and feedstock-rich producer and exporter	Exceptional solar & wind potential; established hydrogen and SAF strategies; growing project pipeline, biomass??	Infrastructure scale-up (CO_2 capture, desalination); distance to markets	**PtL and PBtL (hybrid PtX–biomass);** large-scale export hubs
China	Industrial and technology powerhouse	Manufacturing scale; abundant CO_2 sources; leadership in electrolyser and catalyst supply chains; expanding domestic SAF; renewable energy sources?? demonstration base	Fossil dependence; certification alignment and ESG assurance	**PtL and PBtL (hybrid PtX–biomass);** regional technology supplier
India	Biomass-rich emerging hub and future exporter	Vast agricultural residues; expanding renewables; strong domestic demand base	Water stress; fragmented logistics; policy consistency	**PBtL (hybrid PtX–biomass);** residue-to-fuel production and export potential
Indonesia	Biomass exporter and PBtL corridor partner	Abundant palm & forestry residues; renewable expansion; export connectivity to Malaysia & Singapore and growing hydrogen co-production interest	Deforestation & LUC risks; infrastructure and governance gaps	**PBtL exports;** PtX–biomass corridors with Malaysia & Singapore
Japan	Import-reliant technology and policy leader	Advanced R&D capacity; coordinated industrial ecosystem; leadership in traceability and digital certification platforms; secure aviation off-take market	Limited renewable resource base; import reliance	**PtL imports and domestic technology development** for synthesis and monitoring systems
Malaysia	Biomass and resource bridge country	Substantial palm and forestry residues; favourable water and energy base	ESG risks in residues; moderate policy momentum	**PBtL (hybrid PtX–biomass);** regional bridge to Indonesia and Singapore
Singapore	Finance, trading & digital-monitoring hub	Global logistics & finance expertise; emerging digital sustainability-tracking systems	Minimal domestic resources; high import dependence	**PtL and PBtL imports;** aggregation, certification & trading centre
South Korea	Technology integrator and import hub	High-tech industrial base; active hydrogen and e-fuel innovation	Constrained renewables; reliance on imports	**PtL imports;** technology integration and early domestic PtL demonstration projects
Thailand	Demonstration hub for hybrid pathways	Diverse agricultural residues; maturing renewable capacity; growing R&D interest	Grid flexibility; limited financing for pilots	**PBtL and hybrid PtL/PBtL** demonstration projects

6.2.3. Conclusion and Outlook

This roadmap has shown that the APAC region holds vast potential to become a cornerstone of the global PtX fuel transition — yet realising this potential will depend less on technical feasibility and more on governance, coordination, and investment. Across APAC, renewable energy, biomass, and CO_2 resources are abundant, and several countries already serve as global technology and finance hubs. However, deployment remains constrained by fragmented policies, uneven infrastructure readiness, and gaps in sustainability governance.

A key conclusion is that **no single country can meet all requirements for large-scale PtX deployment alone**.

- **Australia and China** possess the scale and resource endowments to drive production.
- **Japan, South Korea, and Singapore** provide governance, technology, and market leadership.
- **India and emerging Southeast Asian economies** offer substantial feedstock and biomass potential but need stronger safeguards and enabling frameworks.

This complementarity is APAC's greatest strength — if harnessed through deliberate regional cooperation and coordinated market design.

At the same time, **economic feasibility remains the decisive challenge**. The cost gap between PtX and fossil fuels, combined with investment risk and infrastructure bottlenecks, could delay deployment without targeted support mechanisms. Blended finance, regional trade corridors, and long-term offtake frameworks will therefore be crucial to unlock private capital and reduce perceived risk.

Equally, **sustainability is not a constraint but a prerequisite for credibility**. PtX fuels must deliver verifiable climate and social benefits — ensuring low-carbon electricity, sustainable CO_2 sourcing, responsible land and water use, and equitable social outcomes. Strengthening certification schemes such as CORSIA, and aligning emerging regional standards, will be critical steps to ensure that APAC PtX fuels are both market-viable and globally recognized.

Looking ahead, three priority areas emerge for further work:

1. **Country-level deep dives** – Conduct detailed national assessments linking resource mapping, investment pipelines, and regulatory readiness to identify country-specific transition pathways.
2. **Regional infrastructure and trade modelling** – Analyse cross-border PtX supply chains for hydrogen, CO_2, biomass, and electricity, including logistics, cost structures, and governance mechanisms.
3. **Integrated sustainability research** – Expand coverage of social safeguards, biodiversity protection, and emerging issues such as desalination, mining of critical raw materials, and circularity of catalysts.

If advanced collectively, these steps could transform today's fragmented initiatives into a **cohesive and regionally integrated PtX fuel ecosystem**. The next decade will be decisive: choices made by governments, industry, and civil society before 2035 will determine whether PtX fuels remain a niche option — or become a core pillar of APAC's clean-aviation and climate-neutral energy future.

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8 ANNEXES

ANNEX I. COUNTRY-LEVEL SAF POLICY MEASURES IN THE APAC REGION (→ SECTION 2.1)

This annex provides country-level examples of *SAF* policies in the APAC region, grouped into three categories:

1. Direct policies – blending mandates or legally binding targets.
2. Indirect support measures – financial, fiscal, or R&D incentives.
3. Strategies and roadmaps – long-term planning frameworks signalling government intent.

Direct Policies are policies that directly regulate SAF production and use, most commonly through blending mandates or legally binding targets. They provide the strongest market signals by creating demand certainty, lowering investor risk, and accelerating deployment. In the APAC region, only Singapore and South Korea have confirmed blending mandates, while most other countries are still considering targets or pilot goals.

- **Singapore:** Enacted blending mandate[a] – flights departing Singapore must use at least 1 % SAF from 2026, rising to 3–5 % by 2030, under the *Civil Aviation Authority of Singapore SAF Mandate and Levy Scheme*[114].
- **South Korea:** Legislated blending mandate[b] – the *Petroleum and Petroleum Alternative Fuel Business Act*[115] requires a 1 % SAF blend for outbound international flights from 2027[116].
- **Japan:** Proposed blending mandate[c] – the *Act on Sophisticated Methods of Energy Supply Structures* underpins Japan's target of 10 % SAF by 2030, but this remains under consultation with industry and is not yet binding[117,118].
- **Australia:** R&D and project funding – through the *ARENA SAF Funding Initiative* and the *Future Made in Australia programme*, the government supports feasibility studies and project development, but without binding blending targets.
- **Southeast Asia:** Emerging SAF mandates – Indonesia, India, and Malaysia have all announced binding 1 % mandates starting in 2027 (with India rising to 5 % by 2030 and Malaysia targeting 47 % by 2050). Thailand has a non-binding 1 % target from 2026, aiming for 1–2 % by 2030 and 8 % by 2036.
- **China:** Policy under development – No binding SAF mandate yet, but CAAC targets 50,000 t cumulative use by 2025 and is piloting SAF programs and certification systems. A 2–5 % blending mandate by 2030 is widely expected but not yet official.
- **Other APAC markets:** Early-stage goals and voluntary measures – New Zealand is considering voluntary blending goals of 1–5 % SAF but has no binding measures confirmed.

Indirect Support Measures reduce the cost gap between SAF and fossil jet fuel without mandating its use. They typically operate through financial incentives, carbon pricing, loan guarantees, or R&D funding, making SAF projects more viable and attractive to investors. Across APAC, indirect measures are more common than binding mandates but remain fragmented and relatively modest in scale. SAF is often supported as part of broader renewable energy or decarbonisation initiatives rather than through dedicated aviation frameworks. These measures can ease early-stage risks, but their impact depends heavily on long-term policy stability and coordination with stronger demand-creating instruments such as mandates. Some key examples include:

- **Japan:** R&D and feedstock mobilisation – Green Innovation Fund (up to ¥2 trillion / ≈USD 14bn), with allocations for SAF pilots and feedstock development; dedicated grants supporting diversification of non-food biomass residues.
- **India:** Direct subsidies and energy transition incentives – *Production Linked Incentive (PLI) Scheme for Advanced Biofuels* provides capital

a. An enacted blending mandate is already in force or has a confirmed start date in the near term (e.g. Singapore, 2026).
b. A legislated blending mandate has been passed into law but will only apply from a future date (e.g. South Korea, 2027).
c. A proposed blending mandate has been announced by government but is still under consultation or lacks legislative force (e.g. Japan, 2030 target).

support for SAF and advanced biofuels; *National Green Hydrogen Mission (2023)* incentivises green hydrogen and derivatives, relevant for e-kerosene production; *Waste-to-Energy Policy* promotes conversion of bio-waste into intermediates like biogas, syngas, and CBG that could support SAF feedstock supply.

- **Singapore:** Infrastructure and system planning — Sustainable Air Hub Blueprint (2023), combining SAF incentives with broader aviation ecosystem development; National Hydrogen Strategy (2022), centred on hydrogen imports and infrastructure, creating indirect support for synthetic fuel pathways.
- **Australia:** Funding, hydrogen strategy and fuel incentives — State-level grant programmes (e.g. ARENA support for SAF feasibility and pilots); the National Hydrogen Strategy (2019, updated 2022), focused on large-scale renewable hydrogen production and exports, indirectly supporting PtL fuels; a new 2035 national emissions target (62–70 % below 2005 levels) strengthening the climate policy framework[119]; and a new federal production incentive for low-carbon liquid fuels, designed to accelerate domestic SAF and e-fuel deployment[120].
- **China:** Demonstration and resource frameworks —*14th Five-Year Plan for Civil Aviation Green Development* promotes SAF pilots and standard-setting; Waste/Water Pollution Prevention Laws encourage sustainable resource practices relevant for SAF inputs.
- **South Korea:** Resource framework — *Waste Management Act* encourages utilisation of waste streams that could serve as SAF feedstocks.
- **Other APAC markets:** Countries such as Indonesia and New Zealand have discussed voluntary blending goals (e.g. 1–5 % SAF), while also exploring enabling measures such as biomass and waste utilisation policies, though without binding measures.

Strategies and Roadmaps provide long-term direction without immediately creating binding demand or financial incentives. They signal government intent, outline targets, and guide investment planning, but their effectiveness depends on follow-up through mandates or support measures. In APAC, many countries have published strategies that reference SAF, PtX fuels , or broader green aviation goals, but most remain at the planning or consultation stage. Some key examples include:

- **Japan: Sectoral roadmap —** the *GX Strategy (Green Transformation Strategy)* sets long-term decarbonisation pathways, including SAF and PtX fuels , complementing Japan's 10 % SAF target by 2030.
- **South Korea: National roadmap —** the SAF Blending Mandate Roadmap (2025) confirms a blending mandate from 2027, alongside broader aviation decarbonisation goals.
- **China: Planning framework —** the *14th Five-Year Plan for Civil Aviation Green Development* highlights SAF pilots, testing programmes, and standard-setting, while leaving mandates undefined.
- **Singapore:** The **Net Zero Roadmap** for the Singapore public sector envisions achieving net-zero emissions by 2045. It focuses on using alternative energy sources, developing innovative technologies, and designing energy-efficient infrastructures like carbon capture and storage.
- **India: Biofuel roadmap —** the National Policy on Biofuels (2018, updated 2022) sets targets for advanced biofuels deployment and outlines SAF as a long-term pathway, though without quantified blending requirements.
- **Australia: National strategy —** the *Jet Zero Council Australia* and *Future Fuels Strategy* position SAF as part of the aviation decarbonisation mix, focusing on innovation, infrastructure planning, and international cooperation.
- **Other APAC markets: Emerging strategies —** countries such as Indonesia and New Zealand have launched consultations or exploratory studies (e.g. Indonesia's Ministry of Energy SAF discussions; NZ's SAF Roadmap) to assess domestic SAF potential, but implementation remains at an early stage. Vietnam has developed national hydrogen energy development strategy and also published a donor-supported preliminary PtX roadmap[121] (GIZ/BMZ, 2022), which provides directional insights but has not yet been formally adopted by the government. Indonesia's SAF roadmap includes blended mandates slated from 2027 (1 %) and gradual scale-up thereafter. Malaysia has developed a roadmap for hydrogen technology to transform its energy mix and establish itself as a key player in the regional hydrogen economy.

ANNEX II. COUNTRY-BASED RISK ASSESSMENT METHODOLOGY (→ SECTION 3.1)

The country-level sustainability risk screening was carried out using a set of five indicators. The country-level risk assessment is based on the RSB Risk Assessment Tool and RSB Screening Tool, designed to facilitate analysing sustainability risks at both country and operational levels. These tools rely on data from reputable international initiatives such as the Worldwide Governance Indicators, Global Forest Watch database, and United Nations Development Programme Human Development Index. This methodology ensures that the assessment is grounded in robust scientific data. The table below outlines the assessment criteria, data sources, and a description of each indicator, including methodology and retrieval steps.

TABLE 25 METHODOLOGY AND DATA SOURCES USED FOR THE COUNTRY-LEVEL SUSTAINABILITY RISK SCREENING IN APAC, INCLUDING ASSESSMENT CRITERIA, DATA SOURCES, AND DESCRIPTION OF RETRIEVAL AND RISK CLASSIFICATION.

INDICATOR	ASSESSMENT CRITERIA	DESCRIPTION
Deforestation	Are operations located in a country with high levels of permanent-agriculture driven deforestation? The estimate is based on tree cover loss data from Global Forest Watch (GFW)[29].	GFW reports annual tree cover loss by driver at national level. For this study, data for 2022–2024 were retrieved from the GFW database by selecting "tree cover loss by driver" and filtering for the most prominent drivers of deforestation, with "permanent agriculture" Emerging as the leading driver. The share of tree cover loss attributable to permanent agriculture was then calculated for each country. Countries were classified as: <10 % = low risk, 10–25 % = medium risk, >25 % = high risk.
Water stress	Are operations located in a country with high levels of water stress? The estimate is based on the World Resources Institute (WRI) Aqueduct Water Risk Atlas[30].	The Aquaduct Water Risk Atlas assesses the quantity and quality of physical risks to regional water availability. The water stress risk is assessed considering the current scenario as well as the future water stress predictions for 2050 in a business as usual scenario. Risks are classified as low (<10 %), low to medium (10–20 %), medium to high (20–40 %), high (40–80 %) and extremely high (>80 %). This indicator was assessed by observing the map and corresponding coloured legend. It is, though, a qualitative assessment, since every country has regionalised different levels of water stress; therefore, this represents an average and indicative risk for the country. For a specific risk analysis related to a feedstock supply chain, more specific regionalised water stress values should be assessed.
Human and labour rights	Are operations located in a country with poor human and labour rights conditions? The estimate is based on the Worldwide Governance Indicators (WGI) website.[31]	Human and labour rights risk was assessed using Worldwide Governance Indicators (WGI) data on rule of law, regulatory quality, and government effectiveness. According to the RSB risk assessment tool a score of at least 0 in all three indicators would indicate low risk; above -1 but less than 0 in any of the three would indicate medium risk; -1 or below in any three would indicate high risk.

Rural and social development	Are operations located in a region of poverty? The estimate is based on the Human Development Index[32].	The HDI combines data on life expectancy, education, and per capita income to measure national development levels. For this study, country-level HDI scores were retrieved from the UNDP Human Development Reports database (most recent year). For each country, a value is scored between 0 and 1, with a value of less than 0.55 indicating high risk, between 0.55 and 0.69 indicating medium risk, and 0.70 or more indicating low risk.
Food security	Are operations located in a country with high prevalence of food insecurity? The estimate is based on the Global Hunger Index (GHI)[33] website.	The Global Hunger Index (GHI) classifies the severity of hunger on a scale of low, moderate, serious, alarming, and extremely alarming. 2024 data were used in the overall assessment.

ANNEX III. KEY ASSUMPTIONS FOR PTX FUEL RESOURCE QUANTIFICATION (→ SECTION 4.1)

This annex summarises high-level, literature-based process assumptions[5,56,95,122,123] used to derive the indicative resource intensities in Section 4.1. Values are specified per MJ of final SAF (LHV) and, for readability in the main text, are also shown as requirements per tonne (t) of SAF, using an energy content of 43 MJ kg^{-1} (≈ 43 000 MJ t^{-1}) as the conversion basis. Figures represent order-of-magnitude process inputs at the plant gate and are not full life-cycle inventories. Upstream or indirect flows (e.g. virtual water in feedstock cultivation, embodied materials in infrastructure), logistics (grid, CO_2 or H_2 networks) and co-product or recycling effects are excluded. No single CO_2 source or electrolyser configuration is assumed; values reflect a plausible PEM electrolysis baseline for PtL and residue-based feedstocks for PBtL.

Materials accounting and scaling: We distinguish operational inputs that scale with fuel output (electricity, water, CO_2 feedstock; plus hydrogen and, for PBtL, biomass) from consumable critical raw materials (CRMs) (iridium, platinum, nickel, cobalt, copper) used in electrolysers and synthesis catalysts. Capital/structural materials (e.g. steel, concrete) are out of scope for Section 4.1 and screened separately. For comparability, CRM figures assume PEM as baseline; PEM-linked Ir/Pt scale approximately with hydrogen throughput.

PBtL pathways: Literature indicates that carbon efficiency can be raised to ~90 % and above when roughly 0.20–0.25 t H_2 is added per tonne of fuel, depending on configuration[124,125]. Adopting a conservative PBtL setting within that range, this study uses ~0.20–0.25 t H_2 per t SAF for PBtL conversions (see PBtL bullets below). This lowers PBtL electricity and DI-water needs and reduces PEM-linked Ir/Pt compared with PtL.

- **Electricity demand:**

  Hydrogen production via proton-exchange-membrane (PEM) or alkaline electrolysis typically requires around *54–60 kWh per kg H_2*, translating to roughly *0.6–0.9 kWh per MJ of final fuel (LHV)* for PtL pathways, depending on synthesis route, electrolyser efficiency and CO_2 source. This corresponds to approximately *25 000–39 000 kWh (25–39 MWh) per t of SAF*. PBtL systems require less electricity due to lower hydrogen balancing; under the conservative PBtL H_2 setting (*~0.20–0.25 t H_2/t SAF*), the total electricity requirement is *~12 000–20 000 kWh per t of SAF*. Emerging solid-oxide electrolysis (SOEC) with heat integration may further reduce electricity demand by up to 30 percent, though this technology remains at early commercial stages.

- **Water demand:**

  Electrolysis consumes approximately *9 litres of de-ionised (DI) water per kilogram of hydrogen*, plus around *0.05–0.15 litres per MJ of fuel* for cooling, upgrading and balance-of-plant processes. Assuming seawater desalination with a recovery rate of 45–50 percent implies roughly *2 litres of seawater intake per litre of purified water produced*. For *PtL* pathways, the overall DI-water requirement corresponds to approximately *6.0–11.5 m³ per tonne of SAF* (excluding desalination intake). For *PBtL* under the conservative H_2 setting, the overall DI-water requirement corresponds to approximately *4.0–8.7 m³ per tonne of SAF* (excluding desalination intake). Where desalination is used, seawater intake volumes are typically about *two times* the DI-water volumes reported above.

- **CO_2 demand:**

  PtL pathways require approximately *0.07–0.09 kg CO_2 per MJ* of final fuel (LHV), depending on synthesis route and carbon-utilisation efficiency (with Fischer–Tropsch at the higher end). This equates to about *3.0–3.9 t CO_2 per t of SAF*. Capture energy varies by source and technology: for concentrated biogenic or industrial point sources, indicative electricity needs are about *0.11–0.39 kWh per kg CO_2*; for direct air capture (DAC), total electricity demand is in the range *~0.36–0.80 kWh per kg CO_2* (declining over time with technology learning). Depending on the process configuration, a portion of the DAC energy may be supplied as low-/medium-temperature heat. For *PBtL, no external CO_2 input* is required, as the carbon is provided entirely by the biomass feedstock.

- **Biomass demand (PBtL only):**

  Depending on feedstock characteristics and process efficiency, optimised PBtL pathways require approximately *0.05–0.07 kg of dry biomass per MJ of final fuel (LHV)*, corresponding to *2.1–3.0 t of dry biomass per t of SAF*. Feedstocks include agricultural residues (e.g. bagasse, rice straw), palm-oil by-products, forestry residues and the biogenic fraction of municipal solid waste.

- **Hydrogen demand:**

  - Hydrogen is produced on-site for PtL synthesis and for syngas balancing in PBtL systems. Overall consumption is typically *0.010–0.013 kg H_2 per MJ of PtL fuel*, equivalent to approximately *430–560 kg H_2 per t of SAF (PtL)*. For *PBtL*, this roadmap adopts the conservative literature range of *~0.20–0.25 t H_2 per t SAF*, i.e. *~0.0047–0.0058 kg H_2 per MJ of PBtL fuel* (≈ *200–250 kg H_2 per t of SAF*).

- **Raw Materials[a]:**

  - **Iridium (Ir):** Iridium is the key oxygen-evolution catalyst in PEM electrolysers. Typical loadings are about *0.0005 grams per MJ of SAF*, corresponding (for PtL) to roughly *22 grams of iridium per t of SAF*. Under the conservative PBtL H_2 setting (*~0.20–0.25 t H_2/t SAF*), PEM-linked Ir scales to approximately *~8–13 grams per t of SAF*. Global supply is extremely limited—around 10 tonnes per year—making Ir a major bottleneck for rapid PEM scale-up.
  - **Platinum (Pt):** Platinum serves as the hydrogen-electrode catalyst in PEM electrolysers and, in smaller quantities, in some Fischer–Tropsch (FT) and methanol-to-jet (MtJ) processes. Typical use is *0.0003 grams per MJ of SAF*, equal (for PtL) to around *13 grams per t of SAF*; under the conservative PBtL H_2 setting, PEM-linked Pt scales to approximately *~5–8 grams per t of SAF*.
  - **Nickel (Ni):** Nickel is employed in alkaline electrolysers and as a main catalyst in FT synthesis. Average process-level demand is approximately *0.015 grams per MJ of SAF*, equivalent to about *~650 grams per t of SAF*; this is primarily output-linked and therefore similar across PtL and PBtL, subject to specific catalyst formulations.
  - **Cobalt (Co):** Cobalt is used in small quantities in FT and MtJ catalysts, typically *below 0.001 grams per MJ of SAF*, or roughly *~40 grams per t of SAF* (output-linked; similar across pathways).
  - **Copper (Cu):** Copper is required in electrical components, cabling and balance-of-plant systems. Average process-level use is around *0.009 grams per MJ of SAF*, corresponding to approximately *~400 grams per t of SAF* (largely output-linked).

a. Note: If alkaline electrolysis (AEL) is used instead of PEM, Ir and Pt trend towards zero while Ni rises due to AEL electrodes; total energy-water trends remain broadly similar for a given hydrogen throughput.

ANNEX IV. METHODOLOGY TO ESTIMATE APAC RENEWABLE ELECTRICITY CAPACITY (→ SECTION 4.2.1)

This screening evaluates the potential for renewable electricity (RE) production in eight APAC countries. It is based on ten indicators reflecting **current capacity, deployment momentum, resource potential, and system readiness**. The indicators were selected for their relevance to PtX fuels and because consistent, public data was available. They provide a comparative, high-level picture rather than a comprehensive assessment.

Indicators used for the renewable electricity screening:

Current installed RE capacity (GW): Total renewable electricity capacity installed as of 2023, including solar PV, wind, hydro, and other renewables. This indicator provides absolute scale but is not normalised, so it is reported without scoring[126,50].

Current share of low-carbon electricity (%): Share of electricity generation from renewable and nuclear sources in total national generation. This reflects actual penetration of low-carbon electricity in the mix[95,96,122].

2030 projection for RE capacity (GW, % increase to current capacity): Official national targets or international scenarios for installed RE capacity in 2030, expressed also as percentage increase relative to today's capacity[126].

Annual addition of RE capacity (GW/year, % increase to current capacity): Recent average annual additions of renewable electricity capacity, expressed both in GW/year and relative to the current installed base[126,50].

Investment in clean energy (USD/yr, % of GDP): Annual investment flows into renewable electricity generation and enabling infrastructure, expressed in absolute terms and relative to GDP[127].

Solar potential (kWh/kWp/year): Average annual electricity generation per unit of installed solar PV capacity, reflecting natural solar resources[128].

Wind potential (m/s at 100 m hub height): Mean wind speeds at 100 m hub height across suitable areas, indicating wind energy potential[129].

Hydro capacity (GW): Installed hydropower capacity as of 2023, with technical potential considered where data is available [130].

Capacity factor (%): Typical renewable electricity capacity factors (solar PV and wind), representing the average operational yield in each country[131].

National targets (%): Policy commitments and official targets for renewable electricity as a share of generation or capacity by 2030[132].

Grid integration phase (qualitative, 1–5): Expert assessment of power system readiness to integrate variable renewables, scored from 1 (low readiness) to 5 (advanced readiness)[133].

NOTES

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The Roundtable on Sustainable Biomaterials (RSB) is a global membership organisation that drives the just and sustainable transition to a bio-based and circular economy. Our sustainability framework has been developed by our multi-stakeholder membership, and is a uniquely robust and credible foundation for addressing the climate crisis. We use this foundation to develop projects, guidance and new knowledge, and solutions that equip key decision-makers to deliver net-positive impacts for people and the planet.

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