Charting the Path: SAF Ecosystem in Japan

An ICF Report

ICF

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BOEING SMBC AVIATION CAPITAL MITSUBISHI HEAVY INDUSTRIES

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This report was authored by Alastair Blanshard and Alina Viehweber.

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Foreword

Boeing, Mitsubishi Heavy Industries, and SMBC Aviation Capital are proud to have come together to commission this holistic study of Japan's Sustainable Aviation Fuel (SAF) landscape. As representatives from across the aviation sector's value chain, we support the Japanese government's goals of net zero emissions by 2050 and 10% SAF for commercial aviation by 2030.

SAF-certified for use today can reduce lifecycle CO_2 by over 85% and holds the greatest potential to reduce aviation emissions over the next 30 years. We share a common responsibility and mission in our pursuit of decarbonising aviation and believe our partnership in this study demonstrates the cross-sector teamwork needed for Japan to meet its sustainability goals.

We are grateful to the industry stakeholders in Japan who offered their time and local expertise to inform this research. We sincerely thank ICF for ably delivering this report to assess Japan's SAF resources and opportunities within the global economic context. Our hope is that this study helps stakeholders make the best-informed decisions on related policies, investments, and collaboration to build a secure and sustainable SAF ecosystem in Japan.

Leading Organizations

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Photo by Luna Luna

要 旨

日本は、2050年までに温室効果ガスの排出量実質ゼロ（ネットゼロ）を達成すると表明しており、航空業界の脱炭素化達成に向けて2030年までに持続可能な航空燃料（SAF）の使用比率を10%にするという目標を掲げています。本レポートは、日本においてSAFエコシステムを構築し、この目標を達成するために必要な原料、技術、政策について分析しました。

1 主要調査結果の概要

- **航空産業は、日本の経済・社会の繁栄における重要な柱の1つです。**航空産業によるGDPへの年間寄与額は1,180億ドルに及び、30万1,000人の直接雇用を創出しています[1]。航空輸送は地域社会間の架け橋となり、物資や人の移動を担い、投資や経済を支えています。国際航空運送協会（IATA）は、日本の航空輸送が今後20年間で47%成長し、GDPへの寄与額が1,730億ドル増加すると予測していますが、航空輸送の増加に伴い、温室効果ガス（GHG）の排出を削減する対策が求められています。
- **航空機による排出量を削減するために、SAFは極めて重要な役割を担っています。**IATAは、2050年までに航空業界のネットゼロ実現に向けて必要とされるCO_2排出削減量のうち、65%がSAFによる削減と推定しています[2]。SAFは農業残渣や廃棄物などの原料から製造されるドロップイン燃料であり、既存の航空機エンジンを改良することなく使用できます。
- **SAFの国内生産はエネルギー安全保障の改善につながる一方、国内原料は他用途でも利用することで日本に経済的利益をもたらす可能性があります。**日本は世界第5位の石油消費国であり、2022年時点で需要の88%を輸入に頼っています[3]。液化天然ガス（LNG）や原油はタンカー輸送に依存しており、不可抗力による事態が発生した場合には脆弱です。大半のSAF生産施設では、再生可能ディーゼル（RD）やナフサも生産されるため、多くの産業にわたる脱炭素とエネルギー安全保障を支えることになります。
- **日本は国内での専門知識や実績を通じ、先進的なSAF技術に係るリスクを軽減し、技術をグローバルに輸出できます。**「ATAG Waypoint 2050」調査によると、世界で十分なSAF生産能力の構築に必要な投資額は1.1～1.5兆ドルと見積もられています。日本は有数のハイテク輸出国として、国内の専門知識を活用して先進的なSAF施設の初期リスクを軽減し、日本企業が開発した技術を世界市場に輸出する支援を行うことができます。
- **日本は、2030年のジェット燃料需要の10%をSAF（171万キロリットルまたは4億5,100万ガロン）に置き換えることを目標に、2024年半ばまでに規制を導入する計画を立てています。**これは、2050年のカーボンニュートラル達成を踏まえた日本のグリーン成長戦略に沿っており、航空業界によるCO_2排出を大幅に改善する可能性を秘めています。
- **本レポートでは、日本でSAF産業が発展するための原料、技術、政策を分析しました。**日本でSAF供給を確立するためには、(1) 国内原料、(2) 輸入燃料、(3) 輸入原料の3点を検討する必要があります。この分析をもとに、日本でSAFエコシステムを確立するための可能性を紹介します。

[1] iata.org/en/iata-repository/publications/economic-reports/japan--value-of-aviation/
[2] IATA - Sustainable Aviation Fuel (SAF)
[3] Country Analysis Brief: Japan (eia.gov)

- **この分析では、国内原料の極めて高い入手性が示されました。**2050年までに1,100万キロリットル（29億600万ガロン）分のSAFを国内原料で生産できると見込まれています。また、SAFと並行して、副産物として460万キロリットル（12億1,500万ガロン）の再生可能ディーゼルやナフサも生産されます。
- **しかし、日本における生産能力の限界により、2030年までは国内原料由来のSAF生産能力は制限されます。**都市廃棄物（MSW：Municipal Solid Waste）や再生可能エネルギーなど、日本にとって最大の機会となる原料の利用は複雑であり、新たなサプライチェーンや技術、施設が必要となります。これらの開発により、中長期的に国産原料への移行が可能となる一方、短期的にはSAFやエタノールのような精製が容易なバイオ中間体の輸入に依存することになるでしょう。
- **政策による支援が極めて重要です。**SAF施設のコストやリスクを考慮すると、民間資本を呼び込むために一貫した政策的数値が必要です。詳細（2030年前後の水準、持続可能性、不適合時の罰則金）を明確に示しつつ10%利用目標の達成を支援することで、投資が促進され、国内航空会社と海外航空会社の競争条件が平等になります。
- **グローバル市場で国内航空会社が不利にならないよう、政策によって公正な支援を徹底しなければなりません。**航空燃料の価格差により航空会社の業績や市場競争に悪影響が及び、運賃上昇を招く恐れがあります。その結果、地域の接続性や事業競争力が低下する可能性があります。コスト削減の仕組み導入並びに国内及び海外航空会社を政策の対象とせずにSAF利用目標を義務化すると、航空会社がSAFに対する価格プレミアムを負担することになり、乗り継ぎ旅客や関連収益に影響を及ぼすリスクが生じます。

2 日本におけるSAFエコシステムの形成

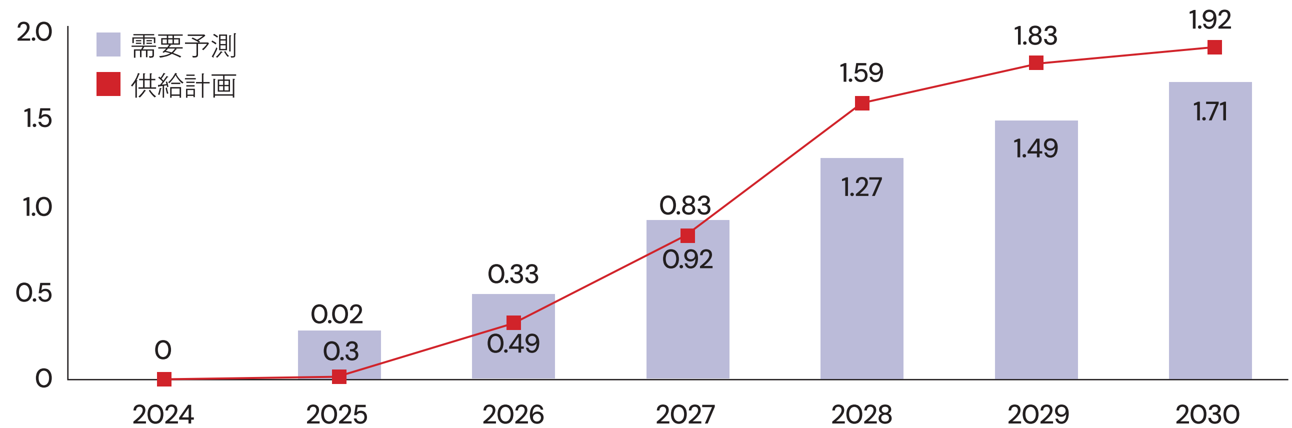
日本におけるSAFエコシステムの形成を導く既存の政策と規制の枠組みとは？

2020年10月、日本政府は2050年までにカーボンニュートラルを実現することを表明し、2030年度までに温室効果ガス（GHG）排出量を2013年度比で46%削減することを中間目標としました。こうした目標の支援に向けて、経済産業省は「2050年カーボンニュートラルに伴うグリーン成長戦略」[4]を策定しました。日本の航空産業からの排出量削減に向けたSAF利用は、この戦略の不可欠な要素です。

2022年4月、経済産業省と国土交通省は共同で、信頼性の高いSAFの国産化を促進する官民パートナーシップを立ち上げ、2022年10月、国土交通省は「航空脱炭素化推進基本方針」[5]（以下、基本方針）を発表しました。基本方針では、航空会社に対して、(i) 国際線におけるCO_2排出量の安定化、(ii) 2030年度までに国内線における単位輸送量当たりのCO_2排出量を2013年度比で16%削減、(iii)2050年までに国際線・国内線ともにカーボンニュートラルを実現、という3つの目標を掲げています。経済産業省は基本方針に沿って、2030年までに高度化法に基づくSAFの新たな利用目標量を設定する計画を発表しました。この目標では、SAFの国内生産を促進するため、2030年までにジェット燃料使用量の10%をSAFに置き換えることが求められています。

経済産業省は、2030年のジェット燃料需要の10%をSAFに置き換える目標を発表
予測供給量は発表された目標を上回る見込み

経済産業省によるSAFの需要と供給の予測（百万キロリットル）



出典：経済産業省

[4] https://www.meti.go.jp/press/2021/06/20210618005/20210618005.html
[5] https://www.mlit.go.jp/report/press/content/001573999.pdf

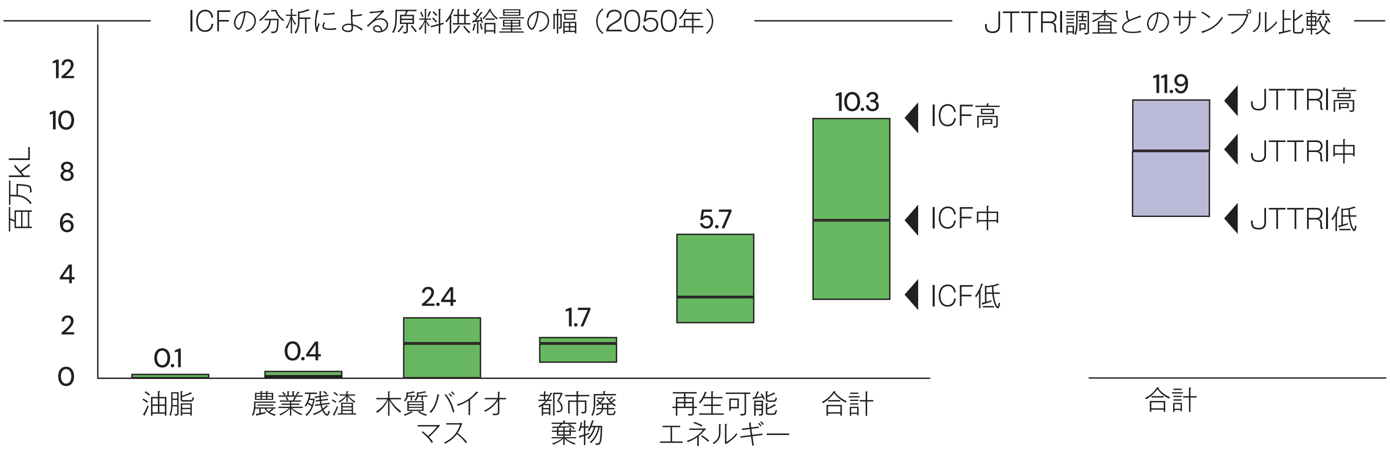
2030年及び2050年のSAF目標を達成するために、どのような国内原料が利用可能か？

SAF利用を通じた日本の航空部門の脱炭素化に向けた最も効率的な戦略を決定する鍵は、利用可能な原料の種類と量を把握することです。この分析では、生物由来及び非生物由来の両原料に焦点を当てています。生物由来原料には、油脂（FOG：Fat, Oil, Grease）、都市廃棄物、農業残渣、木質バイオマス、藻類などの新規原料が含まれ、非生物由来の原料には、リサイクルカーボンや再生可能エネルギーがあります。日本は耕作可能な土地が限られており、食料の輸入量も多いため、食料源と競合する原料は分析から除外しました。

この分析は、グローバル、地域別、国別を含む既存の研究を基に実施しました。とりわけ、運輸総合研究所(JTTRI)[6]、全国油脂事業協同組合連合会　(UCO　JAPAN)[7]、経済産業省[8]などの日本の機関が実施した分析・調査結果を基盤としています。本レポートでは、さらに国内原料の技術面での利用可能性、持続可能な利用可能性及び航空分野への配分に関する詳細を追加しました。これらの情報を用いて、各原料の入手性が(1)　低いシナリオ、(2)　中程度のシナリオ、(3) 高いシナリオの3つのシナリオを構築しました。

各原料の入手性は、原料間の比較がより鮮明になるよう、エネルギーに変換して割り出しました。この分析によると、木質バイオマス、都市廃棄物、再生可能エネルギーなどの先進原料が、日本のSAF生産にとって最大の機会となります。ICFの分析では、SAFの生産量は2050年までに334万キロリットル（8億8,000万ガロン）から1,030万キロリットル（27億2,000万ガロン）の範囲になると推定しました。

ICFは、グローバル、地域別、国別を含む既存の研究を基に、持続可能性と代替用途に関する詳細情報を追加



出典：ICFによる分析、JTTRI。注：両分析は異なるシナリオに基づいているため、数値に幅がある。

以下のケーススタディでは、日本におけるSAF生産用の都市廃棄物の入手性を推定するためにICFが適用した手法をさらに詳しく説明します。

[6] R01_MRI2021_A4縦_報告書_日本語版 (jttri.or.jp)
[7] https://zenyuren.or.jp/document/220407_ucorecycleflow_r3.pdf
[8] https://www.meti.go.jp/shingikai/energy_environment/saf/pdf/003_07_00.pdf

ケーススタディ：日本のSAFにおける都市廃棄物（MSW）の入手性

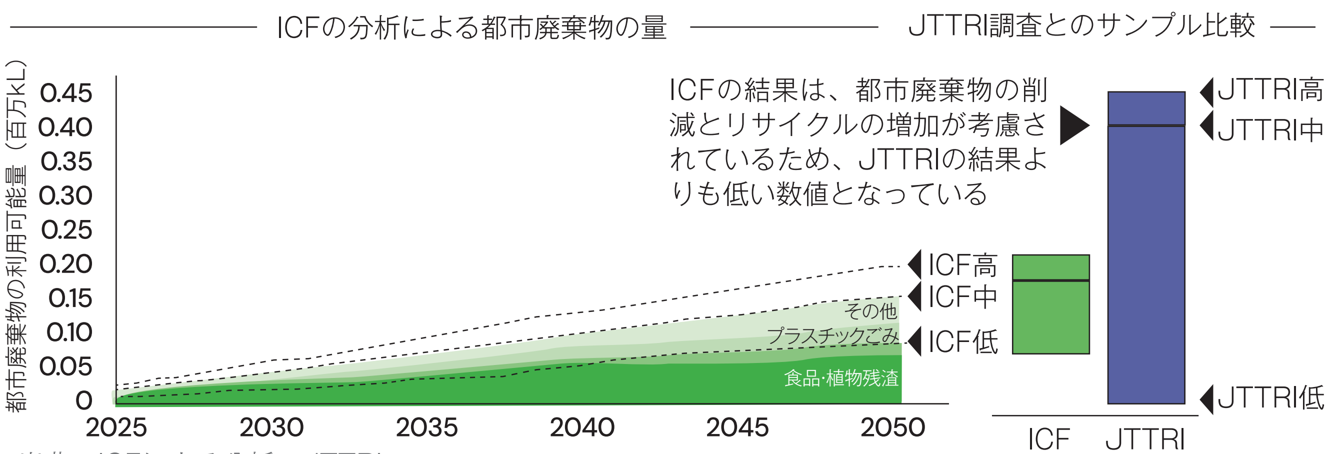
日本には、廃棄物の収集並びにリサイクル、再利用、処分を行う広範なインフラを備えた高度な廃棄物管理システムが整備されています。都市廃棄物を利用したSAF生産は既存の廃棄物管理システムとの統合が不可欠であり、次の3点が機会となります。

- 耐久年数を迎える廃棄物処理施設をSAF施設に置き換える。
- リサイクル不可能な廃棄物を管理する。
- 輸出廃棄物を国内利用に転用する。

SAFの潜在的な生産量は、人口の変化、経済成長、廃棄物回避などの要因を基に廃棄物量の基準値を作成することで評価しました。次に、この基準値を用いてリサイクル率、廃棄物の削減率、焼却からの転換率に基づいて3つの入手性シナリオ（低、中、高）を作成しました。低シナリオは保守的な展開を表し、高シナリオは積極的な展開を表しています。各シナリオの結果は、原料とその後の燃料の炭素強度（CI）を計算できるよう、4つの異なる廃棄物のカテゴリーに分類しました。

焼却容量の低下を考慮すると、短期的な入手性は限られているものの、中長期的には大量の都市廃棄物が入手可能になることが示されました。SAFが熱回収よりも価値の高い選択肢として認識され、SAF生産プロジェクトに政府が補助金を支給することでインフラの再構築を進めることができます。

ICFの分析では、日本の規制を基に、都市廃棄物の削減とリサイクルの増加が考慮されている

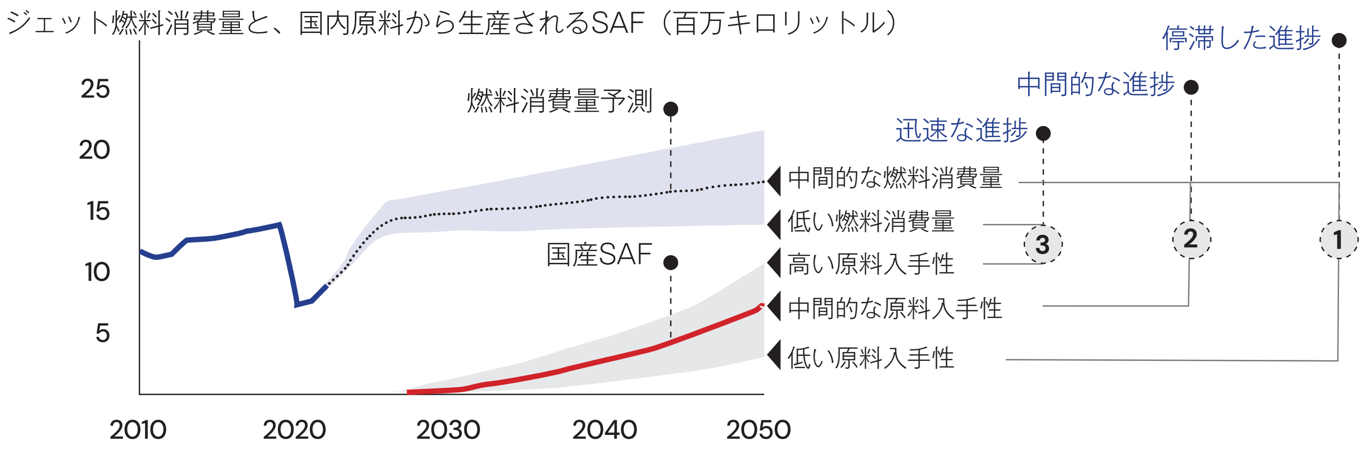


出典：ICFによる分析、JTTRI

SAFの10%利用目標は、ジェット燃料消費量におけるSAFの使用量を示す割合です。SAFの必要量を把握するため、ICFは2050年までのジェット燃料消費量の予測範囲を作成しました。この予測は、これまでのジェット燃料消費量の増加傾向（新型コロナウイルス感染症流行期及びその後の回復を含む）を踏まえつつ、今後の燃料効率の高い航空機導入や運航方法の改善なども考慮しています。これらの予測を基に、国内原料由来のSAF生産機会と燃料消費量の関係を示す以下の3つの産業創成シナリオを作成しました。

1. **産業創成の進捗が遅れた場合：**原料の入手性が低く、燃料消費量は中間的。ジェット燃料消費量の削減と国内SAF生産支援の開発がともに停滞。
2. **産業創成の進捗が中間的な場合：**原料の入手性、燃料消費量ともに中間的。ジェット燃料消費量の削減と国内SAF生産支援を進める開発の基準シナリオ。
3. **産業創成の進捗が迅速に進んだ場合：**原料の入手性が高く、燃料消費量が減少。燃料効率の高い航空機の導入及び運航方法改善に国内SAF生産支援政策が伴う、先進的かつ達成可能な進展。

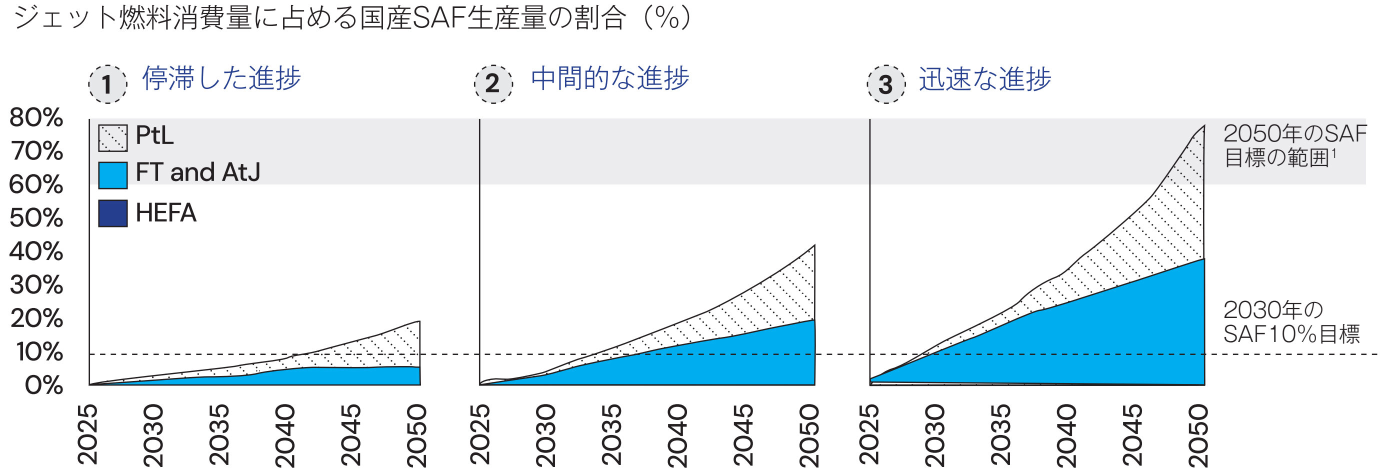
2050年までの燃料消費量に対する国内原料によるSAF生産機会を示す3つのシナリオを作成



出典：ICFによる分析

中・長期的（2050年）には、ジェット燃料の総需要の最大80%を国内原料でまかなえる可能性があります。現時点では、SAFの長期目標に関する発表はありませんが、業界全体で設定された目標（米国では100%、EUでは70%、各航空会社では60%等）を参考にすると、国内原料で需要の80%～100%をまかなうことができる可能性があります。

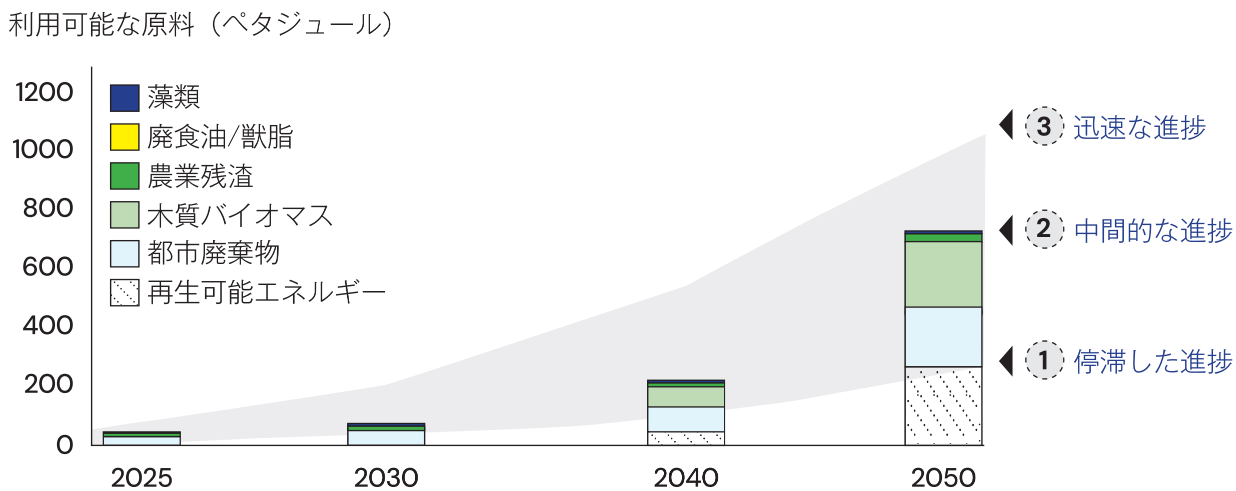
ICFは、政策支援があれば国内原料でジェット燃料需要の最大80%をまかなえると推定



出典：ICFによる分析、[1] 2050年のSAF目標は米国（SAF100%）、EU（SAF70%）、各航空会社の目標を含む。

SAF生産に利用可能な原料を精査し、他原料と比較するためにエネルギー量（ペタジュール）に換算して様々なシナリオを分析した結果、SAF生産量に大きな幅があることが明らかになりました。注目すべきは、都市廃棄物や再生可能エネルギーを含め、炭素排出原単位を大幅に削減できる可能性を示す原料が十分に存在することです。しかし、これらの原料を用いた迅速な普及シナリオの潜在性を活かすためには、支援が必要です。新たなサプライチェーンの開発や技術開発に伴うリスクの軽減、施設の新設、生産の普及促進のために、支援が不可欠となります。HEFAは特に相当量の輸出機会が見込まれますが、他原料にも大きな可能性があることが分析より示唆されました。したがって、先進原料の可能性を最大限に引き出すために、支援体制の構築が何よりも重要です。

利用可能な原料の多くが複雑であり、大規模生産の実現に向けてリスクを軽減する新技術が必要



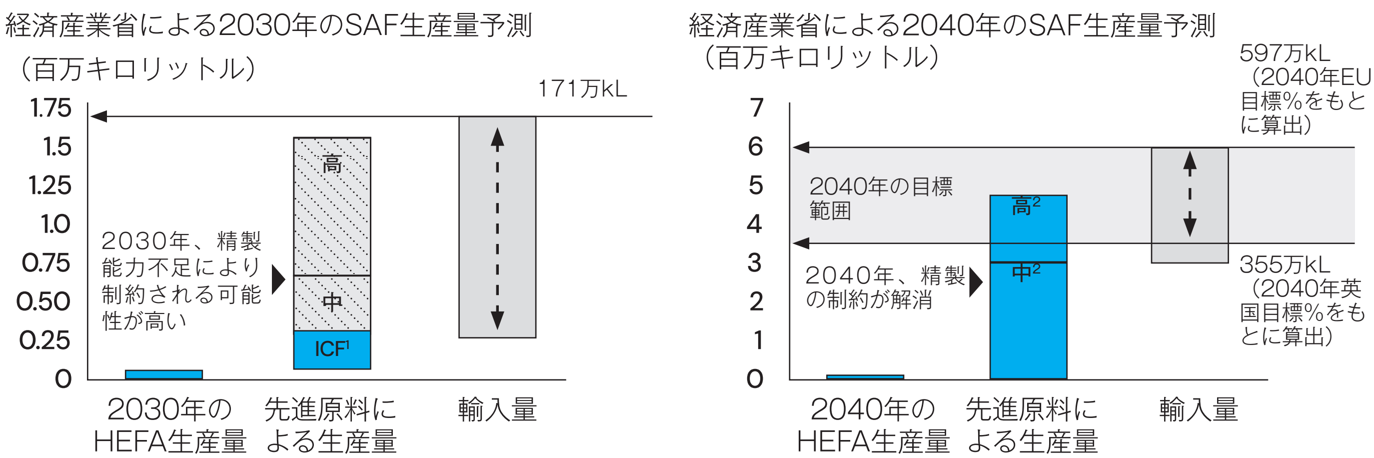
出典：ICFによる分析、藻類と廃食油/獣脂は少量であるためグラフには表示されていない。

国内原料は日本の航空産業の脱炭素化において重要な役割を担う可能性を秘めていますが、迅速な普及シナリオであっても国内原料のみの目標達成は困難です。不足分を埋めるため、原料、中間体、SAF輸入とともに炭素除去などの他分野の対策が必要です。

理論的には、2030年のSAF利用目標を達成する上で十分な国内原料は存在する一方、主な障害はこれらの先進原料をSAFに変換するための新たなサプライチェーン及び技術が必要となること、並びに製造施設の構築を必要とする点です。現在、商用規模でSAFを生産できることが実証されているのはHEFAのみです。AtJ、FT及びPtLといった先進原料の変換技術においては、リスク軽減及び規模拡大に向けてさらなる時間と投資が必要です。

ICFは、2030年までに合計3～5基の先進原料を用いた生産施設（AtJまたはFT）が稼動すると予測していますが、目標とする生産レベルに達するには、原料または燃料そのものの輸入が必要になる可能性が高いでしょう。2040年までには変換技術が成熟すると見られ、また、追加支援により需要の大部分を国内原料でまかなえるようになる可能性があります。日本においてSAFエコシステムを形成する際、精製能力、投資戦略及び政策枠組みの慎重な検討が不可欠です。

先進原料の精製能力に関する予測は不確実性を浮き彫りにし、2030年までの不足分を埋める輸入の役割を強調



出典：ICFによる分析、[1] 2030年の試算は2～3基のFT/セルロース系エタノール施設が本格稼働した場合。
[2] 2040年の試算は技術のリスク軽減に伴う急速なスケールアップを前提としている。

SAF産業は経済成長とエネルギーレジリエンスをいかにして支えることができるか？

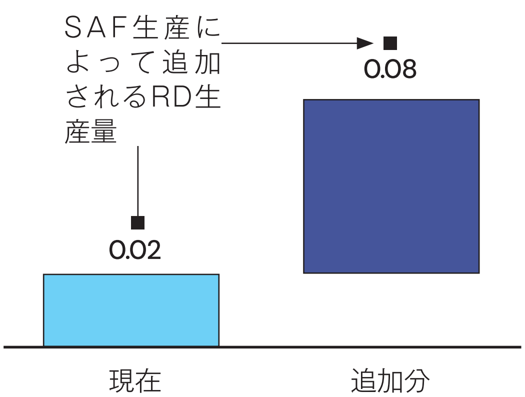
原油や天然ガスなどのエネルギーは、世界で最も多く取引されている商品の1つです。しかし、供給量の50%はわずか5カ国、90%以上はわずか22カ国から供給されているという不均衡が存在し、政治情勢や自然災害の影響を受けやすい脆弱なシステムです。世界有数のエネルギー輸入国である日本はこうした世界的な力学の影響を特に受けやすい状況にあり、SAFと副産物（再生可能ディーゼルやナフサなど）の生産によりエネルギー供給を多様化し、エネルギーレジリエンスと安全保障を向上させる機会が生まれます。

SAF生産の副産物として得られる再生可能ディーゼルやナフサは、道路交通燃料の市場と日本のバイオ燃料目標達成（原油換算で5億リットル）の両方を支えるだけでなく、化学品や素材生産など他産業の支援にもつながります。SAF産業を構築することで、国内の再生可能ディーゼル生産量は2,300万リットル（610万ガロン）から8,000万リットル（2,120万ガロン）へと大幅な増加が見込まれます。

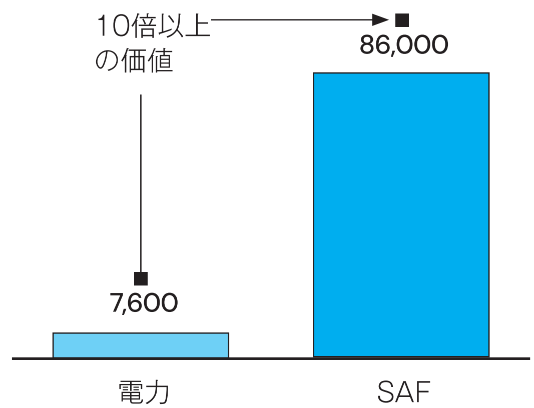
都市廃棄物や木質バイオマスのような多くの原料はすでに他の分野で利用されていますが、この分析では座礁資産を制限しながら、最適な用途へと段階的に移行していくことを考慮しています。例えば、都市廃棄物をエネルギーに変換するために使用される焼却炉は40年の耐用年数を経て廃炉になると予想され、多くは今後10年のうちに耐用年数を迎えます。これにより、原料の利用をSAF生産へ移行することが可能となります。SAFは、エネルギー安全保障と環境面の両方で利点をもたらす高価値製品ですが、こうした利点を得るためには、特定の産業のみが優遇されることがない包括的な政策枠組みが必要です。様々な産業に公平に配分するため、需要と供給の力学に対処するだけでなく他用途からの回収や再配分など、原料調達を支援する仕組み作りが欠かせません。この総合的なアプローチは、政府が目標とするサーキュラーエコノミーやネットゼロの実現に向けて合致しています。

多くの原料はすでに他分野で利用されているが、SAF生産は副産物を含む高付加価値製品を生み出す

国内RD生産量（百万キロリットル）



都市廃棄物のエネルギー換算額（円/トン）



出典：ICFによる分析、USDA Biofuels Annual

SAFエコシステムの形成において、現在どのようなメカニズムが政府を支えているのか？

日本政府はグリーンイノベーション基金などの資金調達メカニズムを用いて、炭素削減のためのイノベーションを支援してきました。この2兆円規模（約144億ドル）の基金は、新エネルギー・産業技術総合開発機構（NEDO）を通じて革新的プロジェクトの研究、開発、事業化を支援しています。SAFは、日本の航空部門の脱炭素化を支援するこの取り組みの重要な支援対象です。グリーンイノベーション基金の一環として、NEDOはSAF及びその他合成燃料や持続可能な燃料を開発するパイロットプロジェクトに1,145億円（約8億3,000万ドル）の助成金を交付しました。これとは別に、経済産業省はNEDOのバイオ燃料技術開発プロジェクトにも51億8,000万円（約3,740万ドル）の追加支援を提供しています。SAF10%利用目標の達成は、グリーンイノベーション基金のようなSAF産業のさらなるリスク軽減と発展を促進する仕組み作りにかかっています。

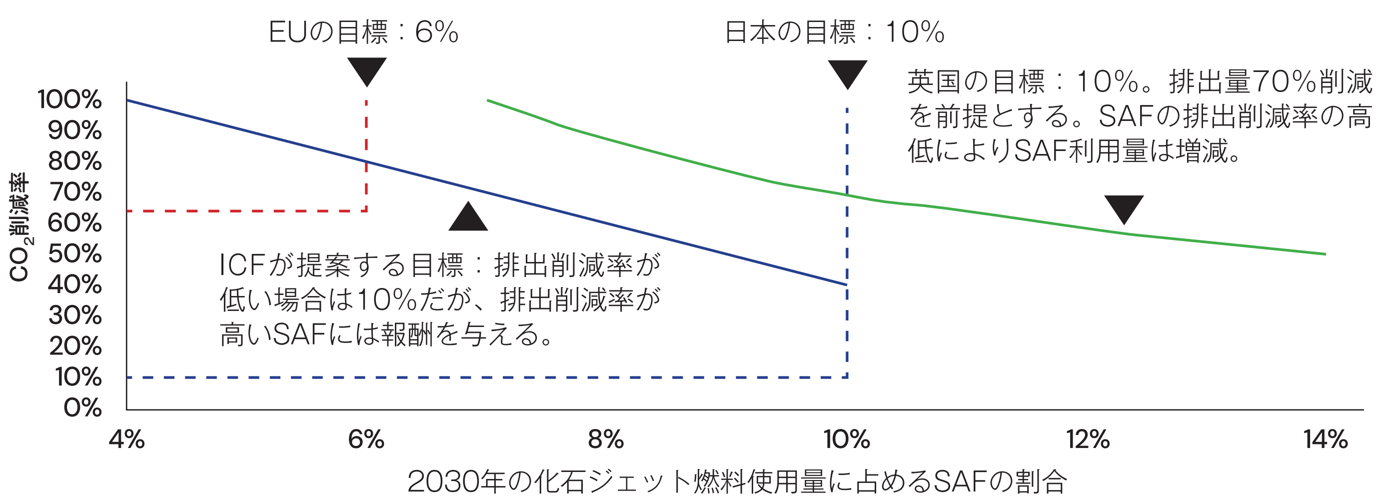
3 進むべき道

SAF産業は、技術開発や投資誘致、旅客への影響軽減のための政策支援を必要としています。ICFは、以下の取り組みにより日本のSAFエコシステム形成が加速する可能性があると考えています。

- **排出量削減の多いSAFに報酬を与える：**日本は、SAF利用量を重視し、CORSIAの持続可能性基準（10%以上の排出量削減を含む）に沿って、2030年に向けて野心的なSAF10%利用目標を表明しています。一方、海外の多くの政策ではSAF使用量が若干低いレベルに設定されていますが、SAFにより排出量がより多く削減された場合には大きな報酬を与えています。例えば、EUでは2030年までにSAF利用率6%を義務付けていますが、排出量削減率65%以上のSAFを対象としています。英国の10%利用目標は炭素強度によって調整され、排出量削減率の高いSAFを使用する場合、目標達成に求められる利用量が低減されます。米国はSAF導入目標を設けていませんが、連邦政府及び州政府の政策はLCFSやSAF-BTC、CFPCを通じてより高い排出量削減に報いるものになっています。このように、日本で使用されるSAFに対しても、炭素強度の低いSAFを利用することで10%の利用目標により大きく貢献できるよう調整係数を適用することを提案します。

  この分析から、日本のSAF10%利用目標を達成するために使用したSAFについて、最小削減率である40%を超える削減率に対して10%毎に+0.25の乗数を付加することを提案します。例えば、SAF利用により排出量を60%削減した場合、+0.5の乗数が付加されます。このSAFを使用して要件全体を満たした場合、総量要件は6.7%（10%/（1+0.5））と計算されます。同様に、平均排出削減率が80%のSAFを利用する場合+1.0の乗数が与えられ、次の図に示すように総量要件は5%になります。

この評価では、10%利用目標への貢献度が高くより大きな排出削減量を達成するSAFに報酬を与えることを提案する



出典：ICFによる分析

この政策案を導入することで日本は世界のSAF利用目標に足並みを揃え、以下の利点を得ることができるでしょう。

a. **日本国内で入手できる原料の大半を占める先進原料を利用した、新たなSAF生産技術の開発支援につながります。**こうした技術や原料は大幅な排出量削減を達成できる一方、高い排出量削減の価値が認識または支持されない場合、より安価な代替品との競争に苦しむ可能性があります。

b. **政府やJAL、ANA、その他の航空会社の脱炭素化目標を支援し、有意義な排出量削減を確実に達成できます。**現在、CORSIAの持続可能性基準に基づくSAFの混合比10%に焦点が当てられていますが、これは実質的な排出量削減達成につながらず、航空会社に割高な費用を負担させることになりかねません。また、（CORSIAが義務付ける）最低10%の排出削減率のみを達成するSAFを用いてSAF10%利用の要件を満たしても、CO_2全体ではわずか1%の削減にとどまり脱炭素化としては不十分です。より高い排出量削減効果を持つSAFに報酬を与えることは、航空関係者が目指す脱炭素化戦略に合致し、より大幅な削減が実現できます。また、実質的な排出量削減効果を得られないまま航空会社がSAFの価格を負担するリスクを防ぐことができます。

- **2040年及び2050年のSAF利用目標を確立する：**今日建設される施設は20～30年間にわたって稼働するため、投資家や生産者に施設の耐用年数にわたって市場が継続するという信頼を与える長期的な目標が重要です。
- **国内航空会社に不利にならない明確なルールを設ける：**SAF利用目標が達成されない際の仕組みを確立することで、海外航空会社にも国内航空会社と同じ目標を課すことができます。この手法はEUと英国で導入されており、道路交通を対象としたバイオ燃料政策にも広く用いられています。
- **次のような供給者を対象とした政策（積極的なインセンチブ）を導入する：**

a. **国内SAF産業の育成：**日本国内のSAF産業はまだ発展しておらず、初期生産者は、産業が成熟している諸外国に比べてコスト面で不利になるでしょう。供給者を対象とした政策により、初期生産者が世界市場で競争力をつけるための知識や技能、専門性を得る支援につながります。

b. **接続性の維持：**多額のコストが顧客に転嫁されると、航空運賃の上昇により接続性が低下し、日本経済の縮小を招く要因となります。オフテイカー、ひいては旅客の負担コストを下げることで、経済への影響を軽減することができます。

c. **国内原料活用に向けた新技術開発：**国内原料の入手性は高い一方、その多くは事業化に新技術が必要です。新技術や設備導入によるリスクを軽減するためには、政府の調査と資金援助が不可欠です。こうした技術を開発することで、世界市場の発展に伴い日本から技術輸出ができる可能性が生まれます。

- **既存政策の活用：**日本のグリーントランスフォーメーション（GX）政策は、カーボンニュートラル達成に向けて様々な産業分野の変革を目指し今後10年間で150兆円（約1兆1,000億ドル）の官民融資を行う投資ロードマップです。この政策は、LNG発電、水素・アンモニア混焼、次世代自動車の支援に利用され、SAF産業発展の支援にも使われる可能性があります。その他政策として、固定価格買取制度（FIT制度）やFIP（フィードインプレミアム）制度、カーボンニュートラルに向けた投資促進税制があります。こうした優遇措置は産業競争力強化法を改正したもので、企業の脱炭素化に向けた設備投資を促進するものです。
- **他産業との連携：**SAFは、水素生産、CO_2回収、再生可能エネルギー、低炭素農業、廃棄物処理など、複数の低炭素産業を加速させる可能性を秘めています。利益を最大化するため、SAF政策の枠組みをこうした他産業の施策と統合する必要があります。

Photo by Nien Tran

Executive Summary

Japan has committed to achieving net zero emissions by 2050 and has proposed a 10% Sustainable Aviation Fuel (SAF) target by 2030 to support the decarbonisation of the aviation industry. This report evaluates the feedstocks, technologies, and policies required to develop a SAF ecosystem in Japan and achieve this target.

1 Summary of key findings

- **Aviation is a key pillar of Japan's economic and social prosperity**, contributing $118 billion to GDP each year and directly employing 301,000 people[1]. Air transport creates bridges between communities, ensuring the flow of goods, people, investment, and economic developments. IATA forecasts Japanese air transport to grow by 47% in the next 20 years, contributing an additional $173 billion to GDP. However, action must be taken to decouple the growth in activity from Japan's greenhouse gas (GHG) emissions.
- **SAF is crucial to reducing aviation emissions.** IATA estimates SAF to contribute to 65% of the emissions reduction needed by aviation to reach net zero by 2050[2]. SAF is produced from feedstocks such as agricultural residues and waste materials and is considered a drop-in fuel, meaning it can be used in existing aircraft engines without requiring modifications.
- **Domestic SAF production would improve energy security, but other uses of the domestic feedstocks may be in Japan's economic interest.** Japan is the fifth-highest consumer of oil in the world, with a reliance on imports to meet 88% of its demand in 2022[3]. Japan relies on tanker shipments of LNG and crude oil, leaving the system vulnerable to force majeure. The majority of SAF facilities will also produce renewable diesel (RD) and naphtha, supporting energy security and decarbonisation across many other sectors.
- **Japan can leverage domestic expertise to de-risk advanced SAF technologies and support global technology exports**. The ATAG Waypoint 2050 study estimates $1.1 to $1.5 trillion in global investment to build sufficient SAF capacity. As a prominent exporter of high technology, Japan can utilise domestic expertise to employ investment to de-risk initial advanced SAF facilities and support Japanese companies to export the technologies developed to the global market.
- **Japan introduced a proposal to replace 10% of the 2030 jet fuel demand with SAF** (1.71 million kilolitres or 451 million gallons), with plans to introduce regulations by mid-2024. This shift, in alignment with Japan's Green Growth Strategy Through Achieving Carbon Neutrality in 2050, has the potential to drive a major improvement in carbon emissions from the aviation industry.
- **This report evaluates the feedstocks, technologies, and policies to develop a SAF industry in Japan.** Establishing SAF supply in Japan involves three key considerations; (1) domestic feedstocks, (2) imported fuels, and (3) imported feedstocks. This analysis evaluated the potential mechanisms to establish a successful SAF ecosystem in Japan.

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1 iata.org/en/iata-repository/publications/economic-reports/japan--value-of-aviation/
2 IATA - Sustainable Aviation Fuel (SAF)
3 Country Analysis Brief: Japan (eia.gov)

- **This analysis showed significant domestic feedstock availability** with capacity to produce 11 million kilolitres (2,906 million gallons) SAF by 2050. Alongside SAF, this feedstock would also produce 4.6 million kilolitres (1,215 million gallons) of renewable diesel and naphtha co-products.
- **However, Japan's limited production capacity restricts the country's ability to process its domestic feedstocks into SAF by 2030.** The feedstocks providing the highest opportunity for Japan, such as Municipal Solid Waste (MSW) and renewable electricity, are complex and require new supply chains, technologies, and facilities. Developing these will allow Japan to shift to domestic feedstocks in the medium/long term, while ensuring uptake in the short term through imported SAF or easily refined bio-intermediaries such as ethanol.
- **Policy support is crucial.** The cost and risk for SAF facilities require a consistent regulatory value to crowd in private capital. Supporting the 10% target with clear details (level before/after 2030, sustainability, buy-out price) will encourage investment and level the playing field between domestic and foreign carriers.
- **The policy must ensure fair support to avoid disadvantages to local airlines in the global market.** Price differences in aviation fuel can harm financial performance, and market competition, and increase fares. This can result in a reduction in regional connectivity and business competitiveness. A mandated SAF target without cost reduction mechanisms or application to both international and domestic airlines risks impacting transiting passengers and associated revenue due to the price premium airlines bear for SAF compared to conventional jet fuel.

2 Developing a Japanese SAF ecosystem

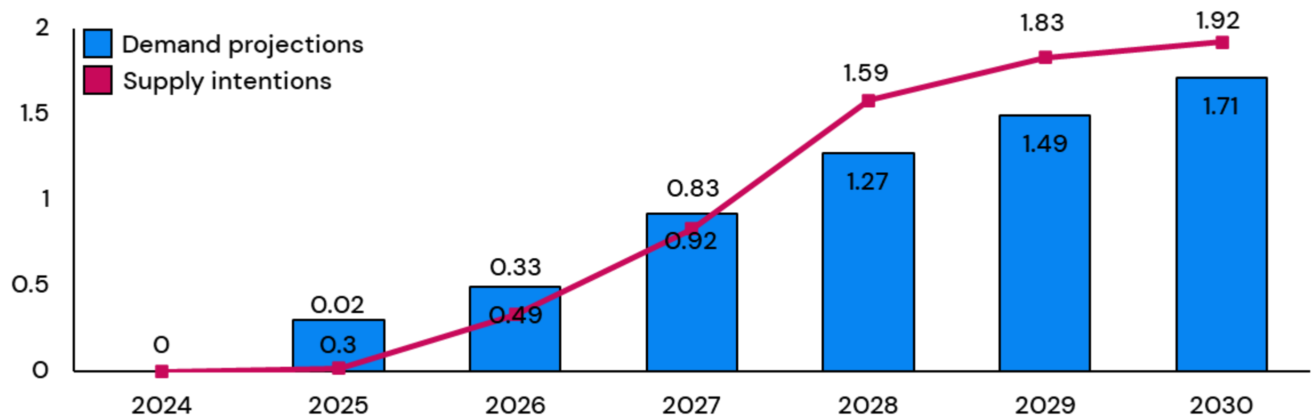
What is the existing policy and regulatory framework guiding the development of a SAF ecosystem in Japan?

In October 2020, the Government of Japan (GOJ) pledged to become carbon neutral by 2050, with the interim goal of achieving a 46 per cent reduction in greenhouse gas (GHG) emissions by 2030 compared to 2013 levels. To support these ambitions, the Ministry of Economy, Trade, and Industry (METI) developed the "Green Growth Strategy Through Achieving Carbon Neutrality in 2050"[4]. The reduction of emissions from Japan's aviation sector utilising sustainable aviation fuel is an integral part of this strategy.

In April 2022, METI and the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) jointly launched a public-private partnership to facilitate the development of reliable domestic production of SAF. In October 2022, MLIT published the Basic Policy for Promoting Decarbonisation of Aviation[5] (hereinafter referred to as Basic Policy). The Basic Policy outlines three targets for airlines: (i) stabilization of CO_2 emissions from international flights, (ii) reduction in CO_2 emissions per unit transport from domestic flights by 16 per cent by 2030 compared to 2013 levels, and (iii) carbon neutrality for both international and domestic flights by 2050. In alignment with the Basic Policy, METI announced plans to set a new target volume for SAF under the Sophisticated Act by 2030. To stimulate domestic SAF production, this target will require SAF to replace 10% of jet fuel by 2030.

METI announced SAF will account for 10% of jet fuel consumption by 2030, with the forecasted supply volume expected to exceed the announced target

METI forecasted SAF demand and supply, METI, Million kL



Source: METI

[4] https://www.meti.go.jp/english/press/2021/0618_002.html
[5] https://public-comment.e-gov.go.jp/servlet/PcmFileDownload?seqNo=0000241937

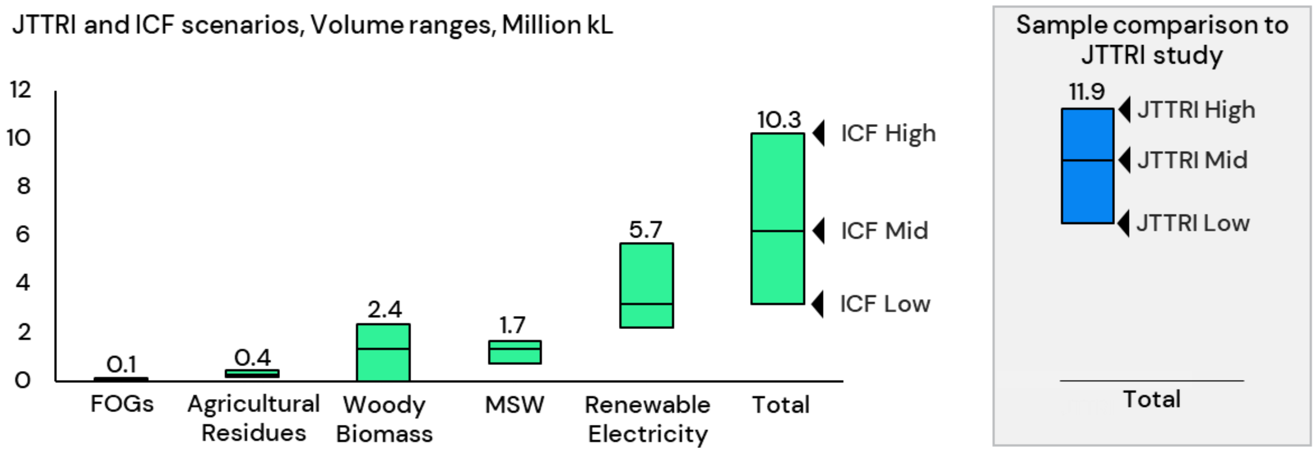
What domestic feedstocks can be used to meet 2030 and 2050 SAF targets?

Understanding the available types and quantities of feedstocks is key to determining the most efficient strategy to decarbonise the Japanese aviation industry through SAF use. This analysis focused on both biogenic and non-biogenic feedstocks. Biogenic feedstocks include fats, oils, and greases (FOGs), municipal solid waste (MSW), agricultural residues, woody biomass, and novel feedstocks such as algae. Non-biogenic feedstocks include recycled carbon and renewable electricity. Due to the limited arable land availability in Japan and considerable imports of food, feedstocks competing with food sources were excluded from this analysis.

This analysis builds on existing work, including global, regional, and country-specific studies. Most notably, this analysis builds on and validates the research conducted by Japanese research institutions such as the Japanese Transport and Tourism Institution (JTTRI)[6], UCO Japan[7], and METI[8]. This report adds additional details on technical availability, sustainable availability, and allocation to aviation of domestic feedstocks. This information was utilised to build three theoretical scenarios; (1) low-scenario, (2) mid-scenario, and (3) high-scenario, for each available feedstock.

The availability of each feedstock was determined and converted to energy to enhance the comparison capability between feedstocks. Based on this analysis, advanced feedstocks such as woody biomass, MSW, and renewable electricity offer the highest opportunity for SAF production in Japan. ICF analysis estimates SAF production to range between 3.34 million kilolitres (880 million gallons) to 11 million kilolitres (2,906 million gallons) by 2050. ICF has conducted a direct comparison with prominent studies like the JTTRI study. This study did not account for emerging feedstocks such as algae for SAF production. Consequently, ICF adjusted the SAF production values between 3.34 million kilolitres (880 million gallons) to 10.3 million kilolitres (2,720 million gallons) by 2050.

ICF builds on the work already completed including global, regional, and country specific studies with additional detail on sustainability and alternate uses



Source: ICF Analysis, JTTRI, Note – both analyses are built on different scenarios resulting in a wide range of values, Conversion: ICF total = 2.7 billion gallons, JTTRI total volume = 3.1 billion gallons

[6] R01_MRI2021_A4縦_報告書_日本語版 (jttri.or.jp)
[7] https://zenyuren.or.jp/document/220407_ucorecycleflow_r3.pdf
[8] https://www.meti.go.jp/shingikai/energy_environment/saf/pdf/003_07_00.pdf

The following case study provides additional detail on the methodology applied by ICF to estimate the availability of MSW for SAF production in Japan.

Case study: Municipal Solid Waste (MSW) availability for SAF in Japan

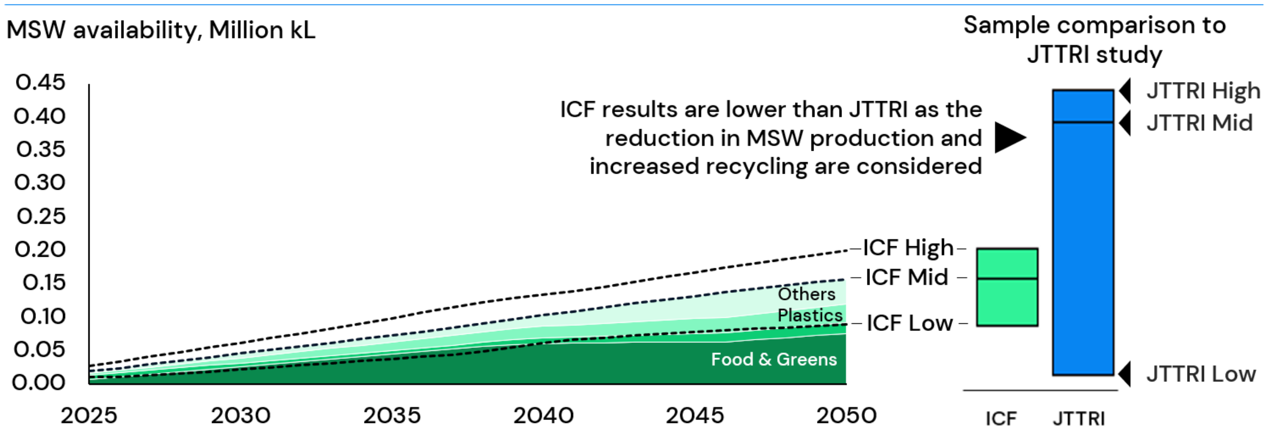
Japan has a well-developed waste management system, with a complete collection of waste and extensive infrastructure for recycling, reusing, and disposal. The use of MSW for SAF production must integrate within this system, with three areas of opportunity:

- Replacing existing waste disposal assets as they reach the end of life.
- Management of unrecyclable waste, i.e. to support existing infrastructure.
- Diversion of exported waste for domestic use.

The potential SAF production is assessed by developing a waste production baseline utilising drivers such as population changes, economic growth, and waste avoidance. The baseline is then utilised to develop three availability scenarios (low, mid, and high), based on the rate of improvement in terms of recycling, waste reduction, and the rate of transition from incineration. The low scenario represents a conservative roll-out, and the high scenario represents an aggressive roll-out. These results utilising the scenarios were segregated into an outcome of four different categories of waste to be able to calculate the carbon intensity (CI) of the feedstock and later-on fuel.

Overall, considering the decline in incinerator capacity, indicates that, despite limited near-term availability, significant MSW volumes could become available over the medium to long term. Considerations include recognising SAF as a higher-value option than thermal recovery, potentially supported by government grants-in-aid for SAF production projects to drive infrastructure replacement.

Aligned with Japanese regulation the ICF analysis on MSW considers reduction in MSW production and increased recycling



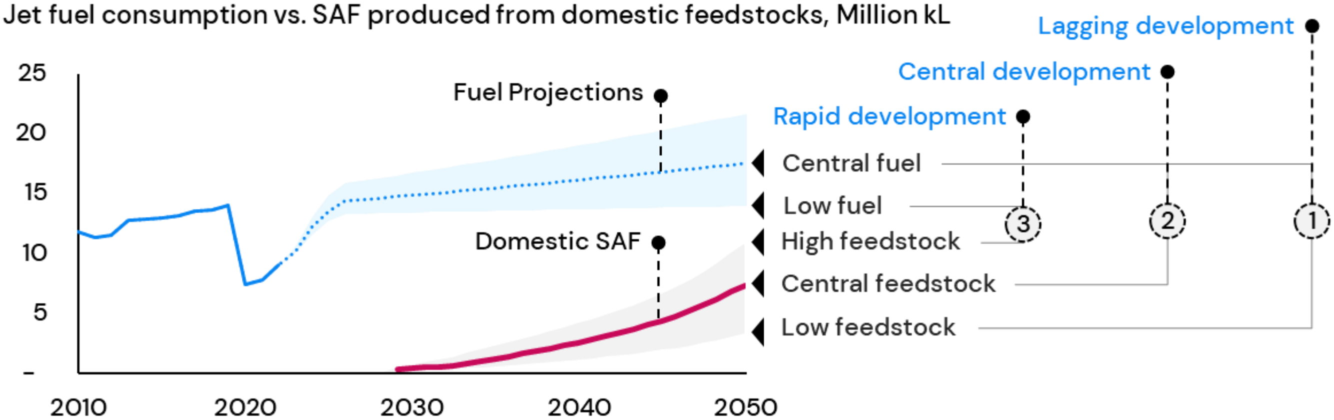
Source: ICF Analysis, JTTRI

The 10% SAF target is a percentage of jet fuel consumption. To understand the required volumes, ICF developed a projected range of jet fuel consumption through 2050. This range outlines the historic growth in jet fuel consumption (including the recovery during and after the COVID-19 pandemic) and assumes various rates of deployment of fuel-efficient aircraft and operational improvements. These projections were utilised to develop the following three scenarios to illustrate the production opportunities for domestic feedstock versus fuel consumption:

1. **Lagging development:** Low feedstock availability and central fuel consumption**.** Stagnation in developments to reduce jet fuel consumption and support domestic SAF production.
2. **Central development:** Central feedstock availability and central fuel consumption. Baseline scenario for developments to reduce jet fuel consumption and support domestic SAF production.
3. **Rapid development:** High feedstock availability and low fuel consumption. Advanced but achievable progress toward the deployment of more efficient aircraft and operational improvement with supportive policy mechanisms to support domestic SAF production.

Three scenarios were developed to illustrate the production opportunities for domestic feedstock vs fuel consumption through 2050

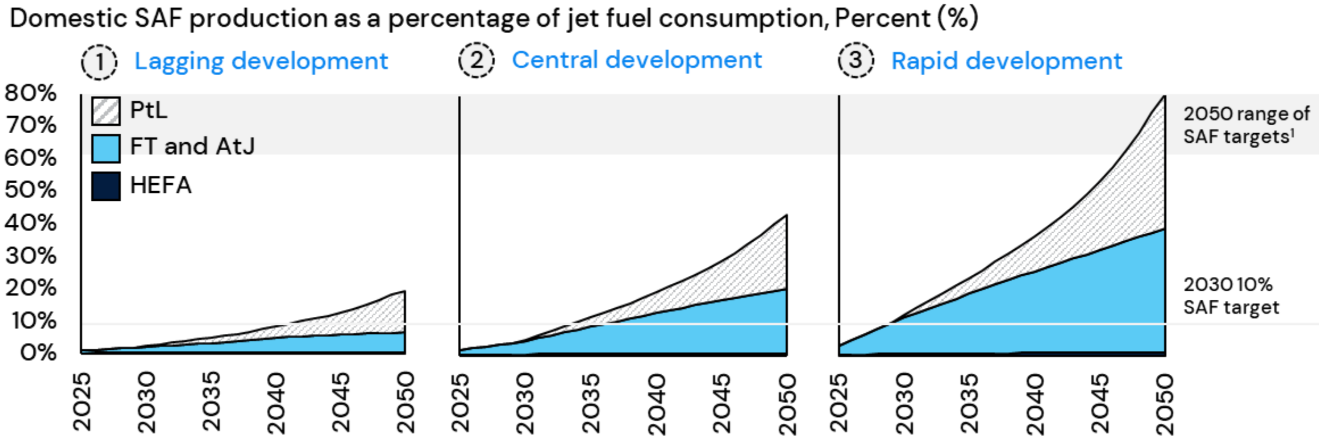
Jet fuel consumption vs. SAF produced from domestic feedstocks, Million kL



Source: ICF Analysis

In the medium to long term (2050), domestic feedstocks could achieve up to 80% of the total jet fuel demand. To date, there has not been an announcement regarding a long-term SAF target. Utilising targets set across the industry (100% SAF target in the US, 70% SAF target in the EU, and 60% SAF target by individual airlines), domestic feedstocks could support between 80% to 100% of the demand.

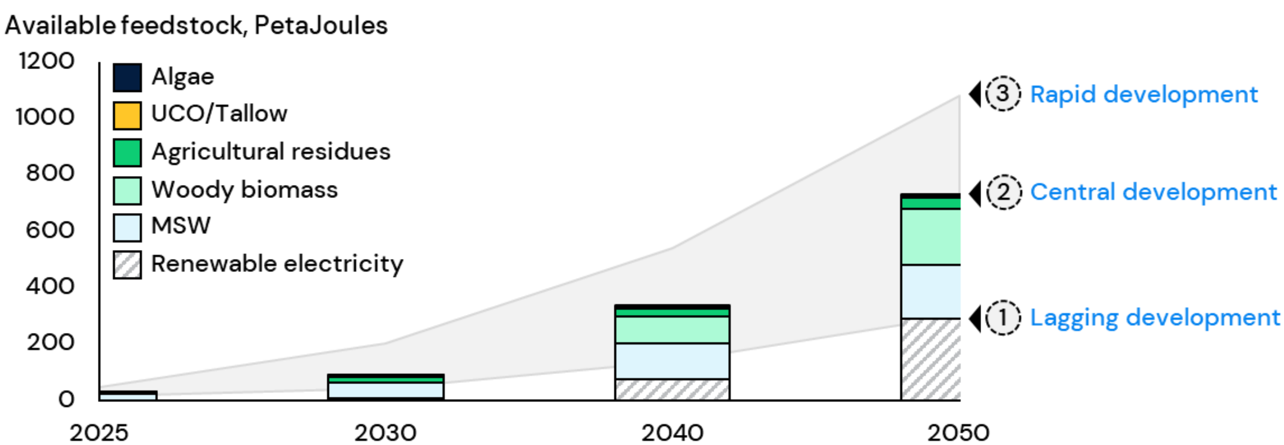
ICF estimates that domestic feedstock is sufficient to meet up to 80% of jet fuel demand with policy support



Source: ICF Analysis, [1] SAF targets in 2050 include the US (100% SAF), the EU (70% SAF), and individual airlines

Examining feedstock availability for SAF production at a closer level, after being converted to energy (petajoules) to allow for comparison with other feedstocks, various scenarios were considered, revealing a considerable range. Notably, there are sufficient feedstocks, including MSW and renewable electricity, that exhibit the potential for significant carbon intensity emissions reduction. However, realising the rapid development scenario potential of these feedstocks requires support. This support is crucial for developing new supply chains, mitigating risks associated with developing these technologies, developing new facilities, and facilitating widespread production. While there is an opportunity for HEFA, particularly with a substantial volume exported, the analysis suggests even greater potential for other feedstocks. Therefore, fostering the necessary support mechanisms is essential to unlock the full potential of advanced feedstocks.

Much of the available feedstock is complex and requires new technologies to be de-risked to allow wide-scale production



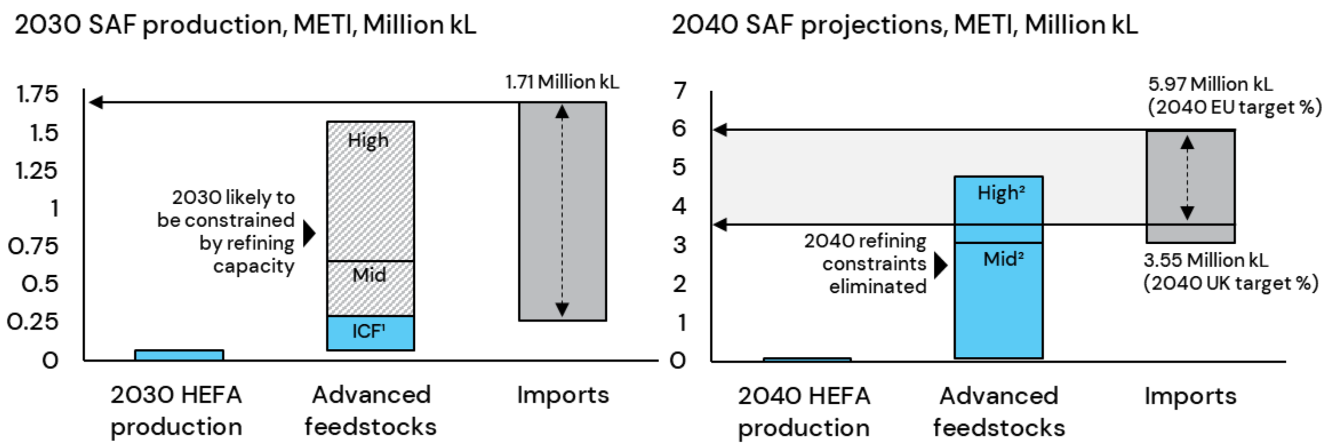
Source: ICF Analysis, negligible volume of algae and UCO/tallow are not visible on graph

While domestic feedstocks can play a significant role in decarbonising Japanese aviation, even the rapid development scenario falls short of the targets. Imports of raw feedstocks, intermediaries, or finished SAF will be required to close this, supported by out-of-sector measures, such as carbon removals.

Although there is a theoretical potential for sufficient domestic feedstocks to meet the 2030 SAF target, the primary obstacle lies with the challenge of requiring new supply chains, technologies, and commissioning refining capacity to convert these feedstocks into SAF. To date, HEFA is the only proven technological pathway to produce SAF at a commercial scale. Technologies to convert advanced feedstocks, including AtJ, FT, and PtL, require additional time and investment to de-risk and scale.

ICF estimates a total of three to five advanced feedstock facilities (AtJ or FT) could come online in Japan by 2030, however, the targeted production levels will likely require imports of either feedstocks or the fuel itself. By 2040, conversion technologies are likely to have matured, and with additional support, these could allow the majority of demand to be met by domestic feedstocks. The development of a SAF ecosystem in Japan demands careful consideration of refining capacities, investment strategies, and policy frameworks.

Projections on the growth of advanced feedstock refining capacity highlight uncertainties, emphasising the role of imports in bridging the gap through 2030



Source: ICF Analysis, [1]2030 estimate is based on 2-3 FT/Cellulosic ethanol facilities in full operation,[2]2040 estimate assumes rapid scale-up as technology is de-risked

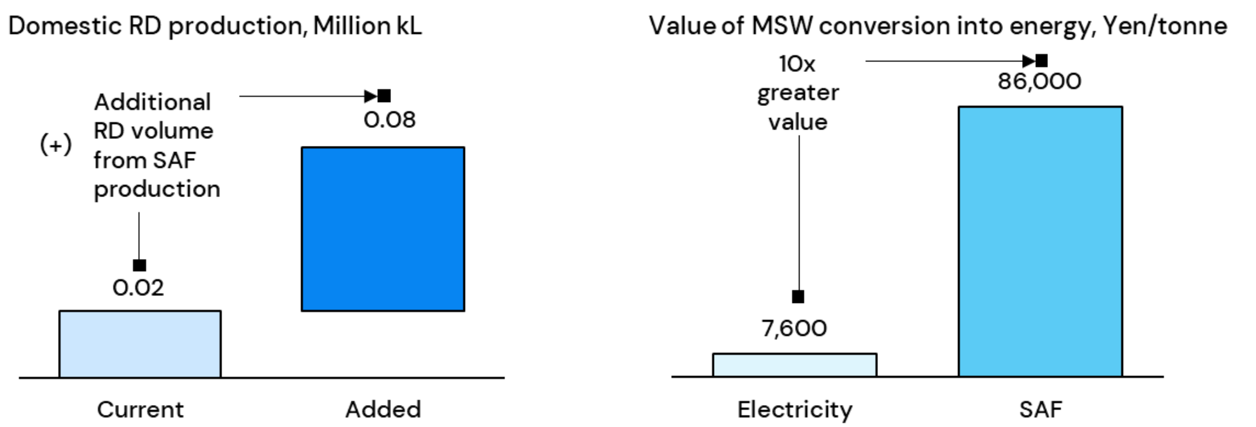
How can the SAF industry support economic growth and energy resilience?

Energy commodities, such as crude oil and natural gas, are among the most traded commodities in the world. However, there is a steep imbalance with 50 per cent of the supply originating from only five countries, and over 90 per cent originating from only 22 countries. This creates a system vulnerable to political and natural events. As one of the world's leading energy importers, Japan is particularly sensitive to these global dynamics. SAF and the production of co-products (such as renewable diesel and naphtha) present an opportunity to diversify the energy supply and improve energy resilience and security.

The production of renewable diesel and naphtha as a co-product to SAF production provides the opportunity to support both the on-road market and the Japanese biofuel target (500 million litres of crude oil equivalent), as well as other industries such as chemical and material production. Building a SAF industry significantly increases the amount of domestic RD produced, from 0.02 million kilolitres (6.1 million gallons) to an estimated 0.08 million kilolitres (21.2 million gallons).

While many feedstocks, such as MSW and woody biomass, are already in use by other sectors, this analysis considers the gradual transition to optimum use while limiting stranded assets. For example, the incinerators used to convert MSW to energy are expected to be retired after a 40-year lifespan, with many reaching their end-of-life by the end of this decade. This allows for the transition of feedstocks to be used for SAF production, which is a higher-value product that supports energy security and environmental benefits. However, achieving these objectives necessitates a comprehensive policy framework with scenarios that avoid favouring one industry over another. Fair distribution across various industries requires mechanisms supporting feedstocks, including collection and reallocation from other uses, as well as addressing supply and demand dynamics. This holistic approach further aligns with government targets related to a circular economy and achieving net-zero objectives.

While many feedstocks are already in use by other sectors, SAF production creates high-value products including the production of co-products



Source: ICF Analysis, USDA Biofuels Annual

What current mechanisms support the government in developing a SAF ecosystem?

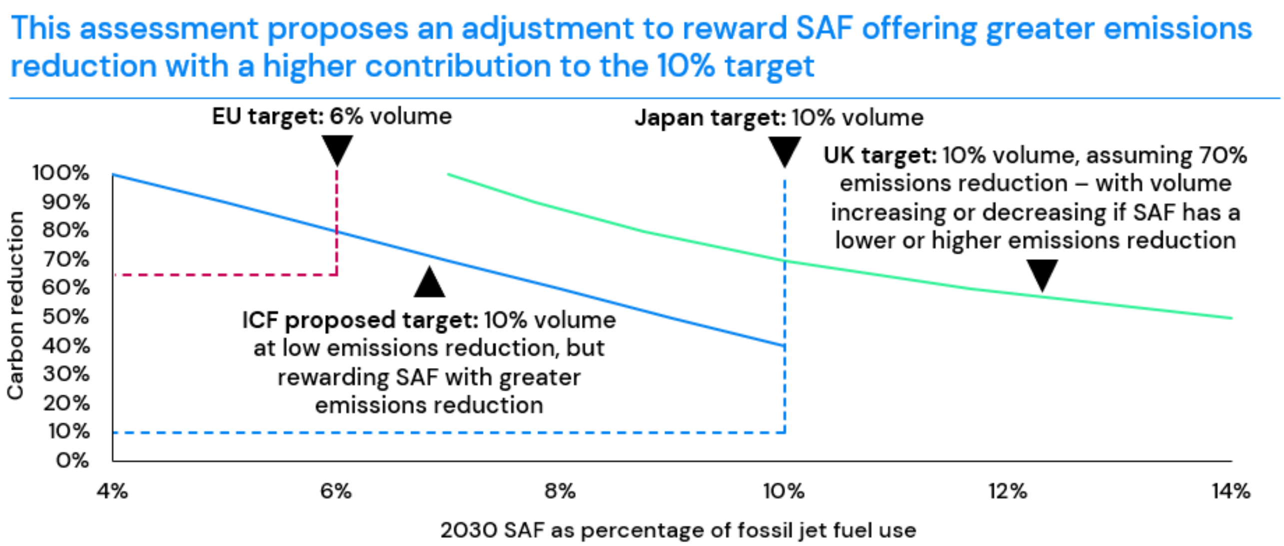
The government of Japan has supported carbon-reducing innovations using funding mechanisms such as the Green Innovation Fund. This 2 trillion yen (approx. USD 14.4 billion) fund supports research, development, and commercialization of innovative projects through the New Energy and Industrial Technology Development Organization (NEDO). SAF is a key target for this initiative to support the decarbonisation of Japan's aviation sector. As part of the Green Innovation Fund, NEDO awarded 114.5 billion yen (approx. $830 million) in grants to pilot projects to develop SAF and other synthetic fuels and sustainable fuels[9]. METI separately provided an additional 5.18 billion yen (approx. $37.4 million) to NEDO's biofuel technology and development projects. Achieving the 10% SAF target will depend on mechanisms such as the Green Innovation Fund to further de-risk and develop the SAF industry.

3 The path forward

The SAF industry requires policy support to develop technologies, attract investment, and reduce the impact on passengers. ICF believes the following initiatives could accelerate the SAF ecosystem in Japan.

- **Reward SAF with a higher emissions reduction:** Japan has proposed an ambitious 10% SAF target for 2030, emphasizing volume and aligning with CORSIA sustainability criteria (which includes a minimum 10% emissions reduction). By comparison, many international policies are set at a slightly lower volume level but provide greater rewards for SAF achieving a higher emissions reduction. For example, the EU mandates 6% SAF by 2030 but has a 65% minimum emissions reduction. The UK's 10% mandate is adjusted by carbon intensity, reducing the volume necessary when using SAF with a higher emissions reduction. While the US does not have a mandated SAF target in place, federal and state policy mechanisms reward higher emissions reduction through the LCFS, SAF-BTC, and CFPC. This analysis proposes that SAF used in Japan is rewarded with an adjustment factor that allows SAF with a lower carbon intensity to contribute more to the 10% volume target.

  This analysis proposes that SAF to meet the Japanese 10% SAF target would receive a +0.25 multiplier for each additional 10% emissions reduction beyond the 40% minimum reduction. For instance, if SAF achieves a 60% emissions reduction, it would be rewarded with a +0.5 multiplier. If the entire mandate is fulfilled using this SAF, the total volume requirement would be calculated as (10% / (1+0.5)) = 6.7%. Similarly, SAF with an average emissions reduction of 80% would receive a +1.0 multiplier, resulting in a total volume requirement of 5%, as outlined in the following figure.



Source: ICF Analysis

The proposed mechanism would align Japan with global SAF targets, and introduce the following benefits:

a. **It would support the development of emerging SAF production technologies that use advanced feedstocks, which make up most of the feedstock domestically available in Japan.** While these technologies and feedstocks can achieve significant emissions reductions, they may struggle to compete with cheaper alternatives if the value of higher emissions reduction is not recognized or supported.

b. **It would ensure a meaningful emissions reduction is achieved, supporting the decarbonisation targets of the government, JAL, ANA, and other airlines**. The current focus on a 10% SAF blend by volume, driven by CORSIA sustainability criteria, might lead to airlines paying a premium without achieving substantial emissions reductions. Meeting the 10% SAF volume requirement with SAF that only achieves the minimum 10% emissions reduction (as mandated by CORSIA) would result in just a 1% reduction across the fuel load, which is insufficient for meaningful decarbonisation. Rewarding SAF with higher emissions reductions aligns with aviation stakeholders' decarbonisation strategies, ensuring a more significant reduction and preventing the risk of airlines paying for SAF without substantial emissions reduction benefits.

- **Establish SAF targets for 2040 and 2050:** A facility built today will continue operating for 20-30 years, so longer-term targets are important to give investors and producers confidence that the market will continue over the facility's lifetime.

- **Establish clear rules to avoid disadvantaging domestic carriers:** Establishing a non-compliance mechanism if the SAF target is not met would ensure that foreign carriers are required to meet the same targets as Japanese carriers. This approach has been implemented in both the EU and the UK and is widely used for on-road biofuel policies.

- **Implement supply-side mechanisms (positive incentives) to**:

  a. **Develop a domestic SAF industry:** The Japanese domestic SAF industry has not yet developed, and initial producers will face cost disadvantages compared to other countries with more mature industries. Supply-side policies can support initial producers to build the knowledge, skills, and expertise that can make the Japanese industry competitive in the global market.

  b. **Maintaining connectivity:** If considerable costs are passed through to customers, the higher cost of flying will reduce connectivity and shrink the Japanese economy. By reducing the cost to off-takers and ultimately passengers, the impact on the economy can be reduced.

  c. **Develop new technologies to use domestic feedstocks:** While there is considerable domestic feedstock availability, many require new technologies to be commercialized. Government research and funding are crucial to de-risk new technologies and facilities. Developing these technologies may allow Japan to export them as the global market develops.

- **Leverage existing policy mechanisms:** Japan's Green Transformation (GX) policy is an investment roadmap for 150 trillion yen (approx. USD 1.1 trillion) of public-private financing over the next 10 years to transform various industrial sectors to achieve carbon neutrality. This policy will be utilised to support LNG power generation, hydrogen/ammonia co-firing and next-generation vehicles, and could be used to support the SAF industry development. Other potential mechanisms include the Feed-In Tariff (FIT), Feed-In Premium (FIP), and the carbon-neutral investment tax incentive. This incentive is a revision of the Industrial Competitive Enhancement (ICE) Act and provides capital investment to support corporate decarbonisation.

- **Alignment to other industries:** SAF has the potential to accelerate multiple low-carbon industries, including hydrogen production, carbon capture, renewable electricity, low-carbon agriculture, and waste management. The SAF policy framework must be integrated with measures in these other industries to maximize benefits.

Contributors

This report was authored by Alastair Blanshard and Alina Viehweber with contributions from Thomas Blanc, Marine Bessoles and Yasar Yetiskin (all ICF).

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Photo by Evgency Tchebotarev

Section 1: Introduction and Japan Context

This report evaluates the feedstocks, technologies, and policies required to establish a Sustainable Aviation Fuel (SAF) ecosystem in Japan, aligning with the country's initiatives for energy security, decarbonisation, and economic growth. Japan's heavy reliance on imported fossil fuels, commitment to carbon neutrality by 2050, and the recent target to achieve 10% SAF by 2030 underscore the urgent need to assess the potential for SAF production and adoption in the country.

Introduction

Aviation is essential to the modern economy, allowing people and trade to seamlessly and connect over extraordinary distances. However, the International Energy Agency (IEA) estimates that aviation is currently responsible for 2% of all human-induced carbon dioxide (CO2) emissions, and up to 3.5% of global warming[10], driving the need to reduce emissions. While the industry has made significant strides in reducing fuel consumption per passenger kilometre, this alone will not suffice to decarbonise the industry. Recognizing this imperative, the industry has committed to achieving net zero by 2050, necessitating decarbonising the fuel produced and consumed, with SAF playing a leading role.

The opportunity for SAF has been recognized by several countries, with the United States, Canada, the European Union, and the United Kingdom leading the way by developing and implementing policies to support SAF production and uptake. In line with this global trend, Japan has taken significant steps to decarbonise its aviation sector. Japan introduced a proposal to replace 10% of the 2030 jet fuel demand with SAF (1.71 million kiloliters or 451 million gallons), with plans to introduce regulations by mid-2024. While Japan has not yet developed continuous commercial-scale production of SAF, the country has made notable progress in this area. For instance, the country's first SAF flight was conducted on February 4, 2021, using SAF produced from cotton clothing to power a Boeing 787-8 aircraft. This development showcased Japan's ability to manufacture SAF using domestic technology, signalling the potential for the country to establish a thriving SAF ecosystem.

Establishing a SAF ecosystem in Japan offers the opportunity to drive down emissions, and enhance energy security and economic growth, enabling sustained connectivity and social benefits. Japan's commitment to SAF production and adoption not only contributes to the global imperative of decarbonising aviation but also holds significant economic value and potential for energy security.

The role of SAF in Japan

Supporting economic value

Aviation is a key driver of global connectivity, economic growth, and technological progress. It plays a vital role in facilitating international trade and tourism by enabling the movement of people and goods across borders.

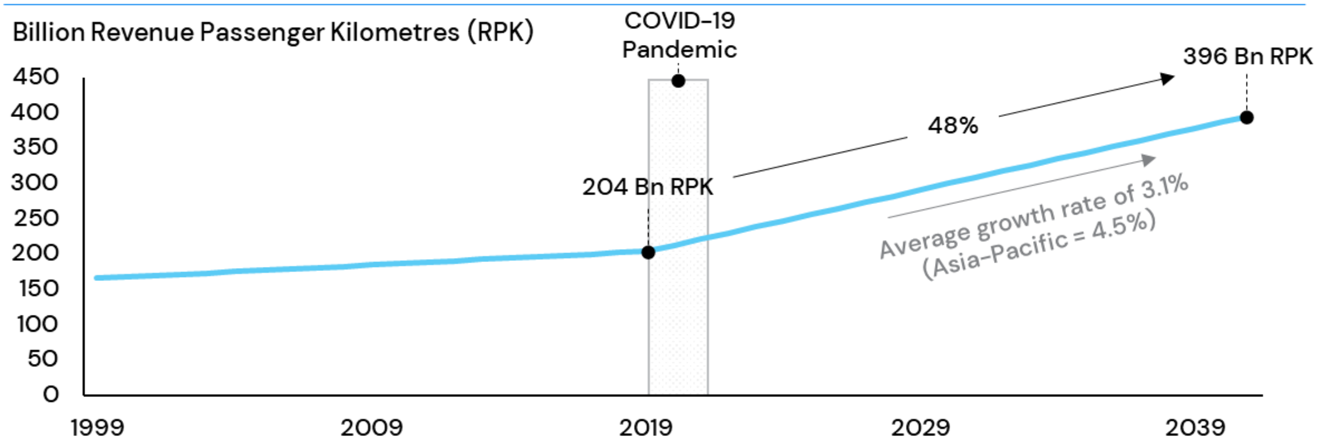
[10] https://www.iea.org/energy-system/transport/aviation

The value to passengers, shippers, and the economy can be seen from the spending of foreign tourists and the value of exports.

In Japan, foreign tourist expenditure and exports are an estimated $USD 34 billion and $USD 798 billion, respectively. The air transport industry, including airlines and the supply chain, is estimated to support $USD 72.1 billion (2.4%) of GDP in Japan. Additionally, the industry supports an estimated 1.4 million jobs through air transport and tourists arriving by air[11].

With ambitious initiatives like the Japanese government's goal to reach 60 million foreign visitors by 2030 (compared to 32 million in 2019), the aviation market in Japan is projected to grow by 48% over the next two decades. This growth is anticipated to translate into an additional 68.9 million passenger journeys, contributing $USD 173 billion in GDP and creating approximately 1.7 million jobs[12].

Japan's RPK's are expected to experience a significant increase, contributing to the country's aviation sector growth and economic development



Source: http://www.jadc.jp/files/topics/174_ext_01_en_0.pdf

The aviation industry is vital to Japan's economic growth and connectivity. However, the industry is also a significant contributor to carbon emissions, making its decarbonisation essential for achieving net-zero goals. A portfolio of solutions will be necessary to reduce emissions, including more fuel-efficient aircraft, operational improvements, new technologies, SAF, and out-of-sector measures. Of all these initiatives, SAF is expected to have the greatest contribution. Estimates suggest the SAF industry could generate up to 14 million jobs worldwide, with around 1.4 million people employed in the production facilities themselves and up to 12.6 million in the construction of facilities, collecting feedstocks (such as used cooking oil and agricultural waste) and the supply chain and logistics[13]. The development and adoption of SAF is crucial for the industry to sustain its growth while reducing its environmental impact, ultimately supporting the transition to a more sustainable sector.

[11] https://www.iata.org/en/iata-repository/publications/economic-reports/japan--value-of-aviation/
[12] https://www.iata.org/en/iata-repository/publications/economic-reports/japan--value-of-aviation/
[13] https://aviationbenefits.org/media/167417/w2050_v2021_27sept_full.pdf

Driving down emissions

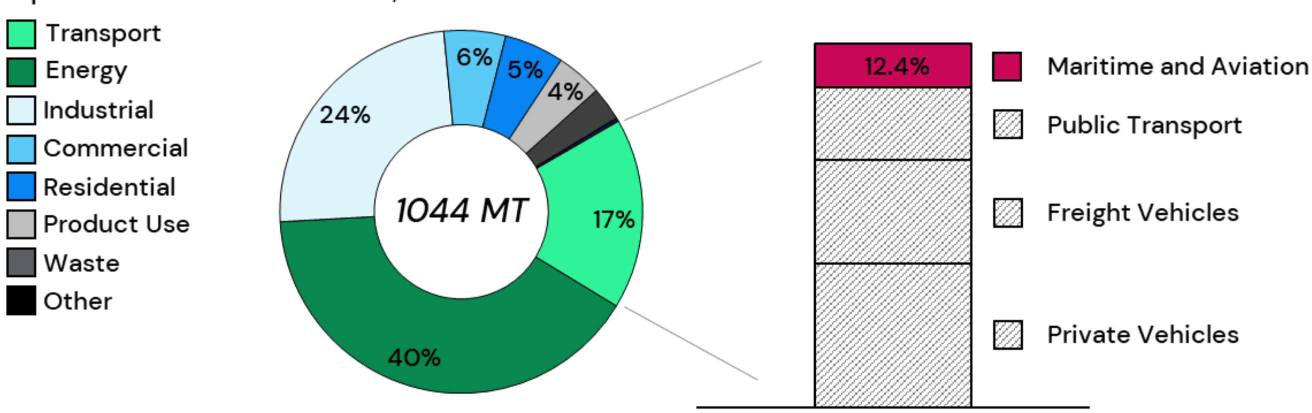
After the adoption of the Kyoto Protocol in 1997, Japan committed to reducing its greenhouse gas (GHG) emissions by 6% by 2020 compared to 1990 levels. Subsequently, under the 2015 Paris Agreement, Japan's Intended Nationally Determined Contribution aimed for a 26% reduction in GHG emissions by the fiscal year 2030 compared to 2013 levels. In October 2020, Japan declared its goal to achieve carbon neutrality by 2050. In April 2021, Japan further pledged to reduce its GHG emissions by 46% by the fiscal year 2030, a significant adjustment from the initial target of a 26% reduction compared to 2013 levels[14].

In support of these aspirations, the Ministry of Economy, Trade, and Industry (METI) developed the "Green Growth Strategy Through Achieving Carbon Neutrality in 2050". This strategy prioritizes the reduction of greenhouse gas (GHG) emissions through the increased utilization of (i) electric vehicles and electro fuels (synthetic fuel or e-fuel) for on-road transportation, and (ii) SAF by the aviation industry.

The importance of decarbonising aviation is underscored by its significant contribution to Japan's GHG emissions and the country's commitment to achieving net-zero emissions. According to the Ministry of the Environment (MOE), Japan's GHG emissions in 2020 totalled 1150 million tonnes of CO2 equivalent, with 1044 million tonnes being CO2 emissions. Emissions from the transportation sector accounted for 185 million MT, or 17% of Japan's CO2 emissions[15].

With transport accounting for 17% of Japanese annual emissions, decarbonising aviation will play an important role in achieving net zero by 2050

Japan's national CO_2 emissions, 2020



Source: https://www.iata.org/en/programs/environment/sustainable-aviation-fuels/, https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Biofuels%20Annual_Tokyo_Japan_JA2022-0109.pdf Japan Ministry of the Environment

While the aviation sector has already achieved a 54.3% reduction in emissions intensity per passenger-kilometre from 1990 to 2018 through the use of more efficient aircraft and operation improvements, fully

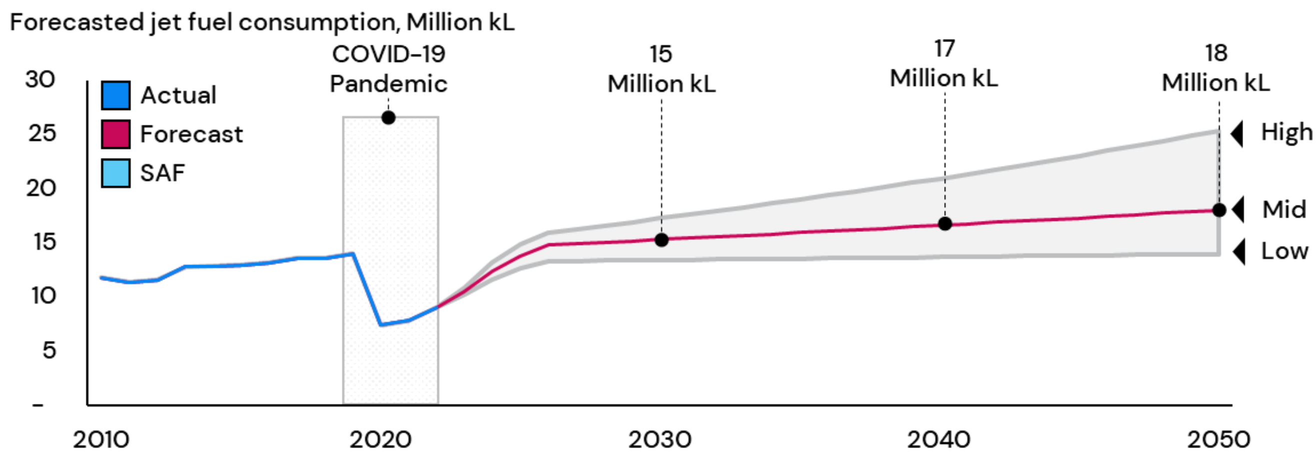
[14] https://www.iea.org/countries/japan
[15] https://www.env.go.jp/content/900505954.pdf

decarbonising the sector will require the energy used to be decarbonised. Three primary solutions are the focus of ongoing efforts: electric, hydrogen, and sustainable aviation fuel (SAF).

As battery energy densities, charging speeds, and safety continue to improve, electric aircraft are expected to be increasingly capable of operating commuter and some regional flights. Nevertheless, these shorter routes account for only 3-4% of emissions from the aviation industry. Hydrogen aircraft may have the potential to address a broader range of markets, but the widespread transition required for aircraft, airports, and fuel logistic infrastructure to utilize hydrogen will limit its impact before mid-century. By comparison, SAF is a drop-in solution, that is interoperable with existing infrastructure and aircraft. Therefore, SAF is projected to play a pivotal role in the decarbonisation of the aviation industry, with the IATA estimating that SAF will contribute 65% of the decarbonisation necessary to achieve net zero by 2050[16].

In this analysis, ICF developed three scenarios (low, mid, and high) based on different rates of deploying fuel-efficient aircraft and operational improvements to determine the required volume of SAF necessary to achieve net zero by 2050 in Japan. In the mid scenario, ICF estimates Japanese jet fuel consumption to reach 18 million kiloliters (4.8 billion gallons) by 2050, requiring an estimated 12 million kiloliters of SAF (3.2 billion gallons) to reach net zero. This value is expected to change as the rate of deployment of efficient aircraft and operational improvements come online. Additionally, this assumes the use of various mechanisms, such as hydrogen and electric aircraft, along with advanced technologies like carbon capture, to mitigate emissions from the remaining fuel consumption.

ICF forecasts annual jet fuel consumption to reach 18 Million kL by 2050 assuming a mid-scenario



Source: ICF analysis

Developing a domestic SAF ecosystem provides additional support to decarbonising other hard-to-abate sectors. Every SAF facility produces co-products of renewable diesel and naphtha, which are important to reduce emissions in heavy transport, agriculture, industry, and petrochemicals. This allows domestic production

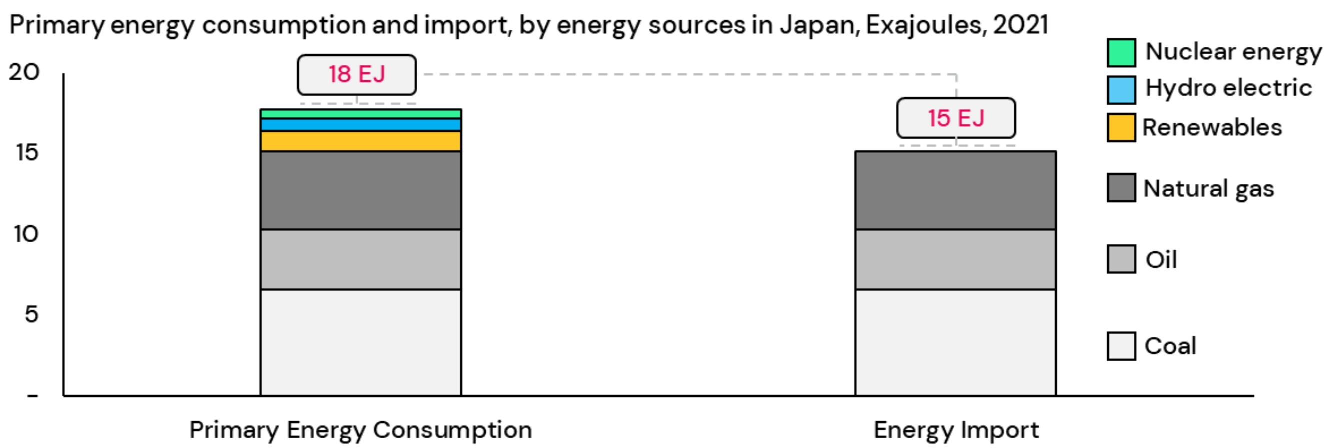
[16] https://www.iata.org/en/iata-repository/pressroom/fact-sheets/fact-sheet---alternative-fuels/

of SAF and co-products to support energy security and contribute to the Japanese biofuel target (500 million litres of crude oil equivalent).

Ensuring energy security

In 2022, Japan ranked as the fifth-highest consumer of oil globally[17]. As an island country with limited domestic resources and no international gas pipelines or electricity connection, Japan is reliant on imports to meet its demand. Following the Great East Japan Earthquake, the degree of dependence on fossil fuels reached a peak of 94% in 2014. The restart of nuclear energy production, expansion of renewables, and lower energy demand have since reduced the demand to 88% in 2019[18]. An ICF analysis determined a further reduction by 2021, with 85% of Japan's primary energy sources being met with imports. Additionally, Japan's energy self-sufficiency ratio is lower than many other OECD countries, at 12.1% (20.2% before the Great East Japan Earthquake) compared to an average of 165% in 2019[19]. The heavy reliance on imports makes Japan vulnerable to international energy market fluctuations from geopolitics, natural disasters, and other uncertainties.

85% Japan's primary energy sources are supported by imports



Source: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2022-full-report.pdf, ICF analysis

To address its energy security challenges, Japan approved the Sixth Strategic Energy Plan[20] in October 2021. This plan is designed to guide the country's energy policy towards achieving carbon neutrality by 2050 and addressing the challenges in its energy supply-demand structure. It aims to double the use of renewable energy for electricity generation from 2019 to 2030, with a target for renewables to account for 36-38% of power supplies in 2030.

Liquid fuel refining has notably declined in Japan, driven by reducing demand (mostly from the on-road sector) and marked by the closure of several refineries. Notable instances include the recent shutdown of ENEOS's

[17] Country Analysis Brief: Japan (eia.gov)
[18] Japan 2021 - Energy Policy Review (windows.net)
[19] https://www.enecho.meti.go.jp/en/category/special/article/detail_171.html
[20] https://www.meti.go.jp/english/press/2021/1022_002.html

Wakayama facility and decreased output from their Nigeshi facility. Idemitsu Kosan's decision to close its Yamaguchi facility further highlights the factors contributing to this decline. The trend aligns with a reduction in gasoline consumption, predicted by METI to decrease by 2.4-2.6 per cent through 2027 due to increased fuel efficiency in new vehicles and the transition to electric vehicles.

The availability of unused assets, such as abandoned refineries, presents a strategic opportunity to convert these facilities into renewable fuel production sites. Such conversions prove to be faster and more cost-effective than building new greenfield facilities, leveraging existing infrastructure and sustaining jobs. Successful global examples, including TotalEnergies' Grandpuits facility in France and Phillips 66's facility in Rodeo, California, underscore the viability of this approach. However, to reinvigorate existing facilities and utilize them for renewable fuel production, a meaningful shift in policy focus to build the additional infrastructure, expertise, and workforce will be required.

Japan's vibrant aviation and energy sectors are crucial to the economy and connectivity of the islands. The government has committed to reducing emissions and has made strides to develop the necessary policy. Understanding the resources, ecosystem, and opportunities is essential to developing the strategy, and we hope the evaluation laid out in this report can support these next steps.


Photo by Dennis

Section 2: The feedstock opportunity

1 Methodology

Review of existing studies on feedstock availability

This literature review informs the requirements of a robust feedstock assessment, reducing duplication and adding depth to analysis that has already been done by other organisations. By understanding the context of other studies, ICF can better place the results of the analysis within this field of research and support an informed comparison between the results of this analysis and others.

The identification of the following three key aspects ensures that the results from this study not only adhere to best practices but also maintain comparability with other research endeavours:

- **Use of comparable units.** The reviewed studies gave the results in many different units, including dry tonnes, wet tonnes, energy content, and tonnes of SAF that could be produced. Each is reasonable for a given context, with feedstock typically measured and sold in tonnes, the energy content driving the facility specifications, and the volume of SAF crucial for the role the feedstock can play to decarbonise aviation. However, this fragmentation can make it challenging to compare feedstocks and studies. Wet tonnes depend on the moisture content, and dry tonnes can have different implications between feedstocks. The volume of SAF can vary depending on the product slate (portion of RD and naphtha) produced. To ensure the results from this study are comparable, each feedstock will be evaluated as dry tonnes and then consolidated using the energy content and measured in petajoules. The potential volumes of SAF will be estimated based on potential product slates.

- **Defining the level of availability that the feedstocks are evaluated against.** While many of the studies were unified in their goal of identifying the available feedstock, the definition of availability varied; some studies considered the total volume of feedstock that could be obtained, while others also accounted for volume that would be unsustainable or uneconomic to obtain. Some further accounted for the volumes that would be used by other industries and would therefore be unlikely to be available for SAF production.

- **Using scenarios to show the potential range of uncertainty.** The results from each study showed considerable variation, especially as a result of different assumptions. For example, the global IEA *Net Zero by 2050* report estimates c. 100 EJ of bioenergy availability, while the ETC *Bioresources within a net-zero emissions economy* estimated a conservative range of c. 50 EJ – a difference of 100%. The main drivers of this difference are the assumptions and forecast changes in other industries, such as land use for meat production and food waste. While sensible ranges can be estimated, there is considerable uncertainty. To ensure that future uncertainty is captured, this analysis will evaluate three scenarios, with a mid-scenario estimate supported by high and low ranges, and the drives that could lead to each.

Additional information regarding the comparison to existing studies is available in the Summary section of this report, offering a more comprehensive insight into the subject matter.

Feedstock selection

To structure this assessment, ICF utilised the CAAFI system of feedstock classification, which categorizes available feedstocks into five distinct groups: (1) Fats, Oils, and Greases (FOGs), (2) Cellulose, (3) Carbohydrates and Sugars, (4) Industrial waste streams, and (5) Electricity (not included by CAAFI, but an important extension to reflect the increasing focus on PtL SAF, particularly in the EU). Within these categories, CAAFI lists at least 135 different possible feedstocks[21], which is likely to grow as additional pathways are certified and technology continues to develop.

ICF prioritized feedstocks that are aligned with guidelines that are developing across the aviation sector, such as the ICAO framework utilised for CORSIA. The appeal of each feedstock is predominantly influenced by its environmental qualities, conversion feasibility, and cost, while limitations in environmental sustainability and competition for resources will place constraints on the aviation industry's long-term utilisation potential. For this analysis, the feedstocks were selected based on their (1) availability to aviation, (2) sustainability criteria, and (2) potential cost. Based on these considerations, this analysis focused on both biogenic and non-biogenic feedstocks. Biogenic feedstocks include fats, oils, and greases (FOGs), municipal solid waste (MSW), agricultural residues, woody biomass, and novel feedstocks such as algae. Non-biogenic feedstocks include recycled carbon and renewable electricity. Due to the limited arable land availability in Japan and considerable imports of food, feedstocks (such as crops) competing with food sources were excluded from this analysis.

Table 1: Feedstock considerations for Japan

Feedstock category	Sub-category	Example feedstocks	Conversion pathways
Biogenic feedstocks			
Waste and residue lipids	N/A	UCO and Tallow	HEFA
Agricultural residues	N/A	Corn stover, rice residues, bagasse	Gas/FT or AtJ
Woody biomass	N/A	Forestry coppice, slash, thinnings, offcuts	
Municipal solid waste	N/A	Black bin and industrial solid waste	
Non-biogenic feedstocks			
Renewable fuels of non-biogenic origin (RFNBO)	Industrial waste gases	Waste carbon gases from industrial plants	Gas/FT or AtJ
	PtL (H2 from electrolysis and CO2 from DAC)	Renewable electricity	

These categorizations laid the groundwork for this analysis and the comprehensive assessment of feedstock viability in the context of sustainable SAF production in Japan.

[21] https://www.caafi.org/focus_areas/feedstocks.html#potential

Feedstock availability

Feedstock availability is one of the key considerations for the future SAF industry, as it directly impacts the volume and specifications for SAF technology opportunities in each region. Feedstock availability is often calculated with different framing, assumptions on sustainability, competing uses, and economic or logistical factors. ICF uses a framework to consider feedstock according to three stages, as described below:

- **Technical availability** of feedstock refers to the total amount of potential feedstock available in a region. This includes availability for any use, from construction to industry and energy. This availability is typically driven by climate and economic factors.
- **Sustainable availability** reduces the total possible feedstock supply by the portion that would be unsustainable to collect or produce. For example, some agricultural wastes must be left in the field to protect soil quality, and the fossil portion of MSW should be avoided if seeking a meaningful GHG reduction. Deducting the unsustainable quantity from the technically available feedstock gives the sustainably available feedstock quantity.
- **Allocation to the aviation industry** refers to the utilisation of feedstock by competing industries. For most feedstocks, SAF production represents just one of its uses, as feedstocks can be used in alternative fuel production (biodiesel), in the chemicals industry (naphtha), in energy production, or other sectors. Therefore, only a portion of the sustainably available feedstocks are typically available to the aviation industry. This stage is the least certain, as many other industries are looking to expand the use of these renewable feedstocks to also decarbonise, so this step sometimes justifies a scenario analysis.

This information was further utilised to build three scenarios to determine the feedstock availability in Japan. These scenarios are as follows:

- **Low-scenario:** Conservative biogenic feedstock estimations, and delayed penetration of advanced technologies required for PtL SAF production.
- **Mid-scenario:** Balanced scenario with baseline biogenic feedstock estimations, and balanced penetration of advanced technologies required for PtL SAF production, in line with optimistic but easily achievable expectations.
- **High-scenario:** Ambitious scenario with optimistic biogenic feedstock estimations, and rapid penetration of advanced technologies required for PtL SAF production.

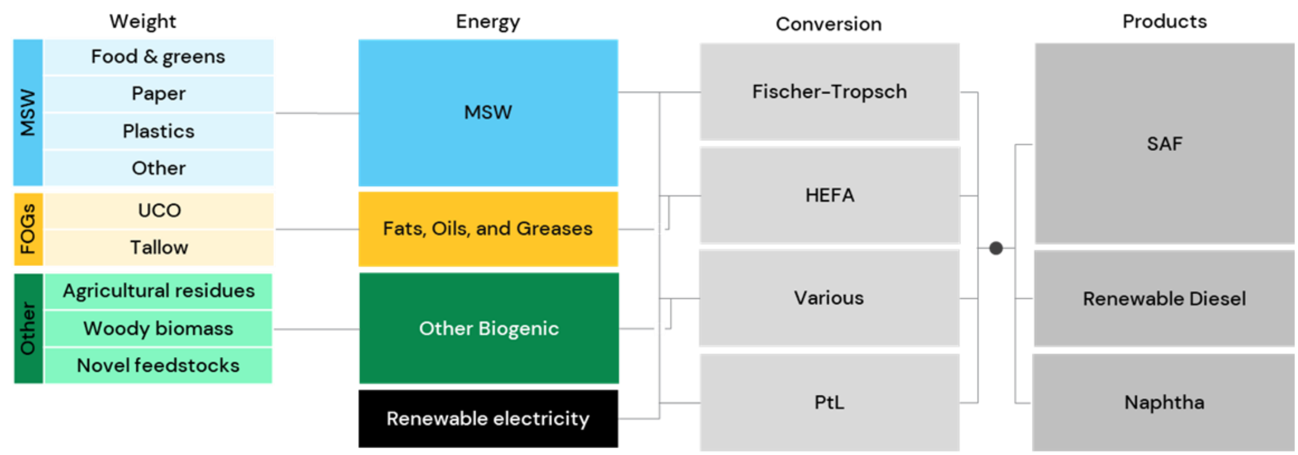
It is important to note that these scenarios were adapted to determine the availability of each respective feedstock as detailed later in the report.

SAF production

The analysis encompassed the entire lifecycle of SAF production, evaluating feedstocks, conversion technologies, and co-product utilization. This comprehensive assessment is crucial for understanding the environmental and economic implications of the entire process. The study estimated feedstock availability, considering factors such as existing uses for feedstocks, anticipated deployment rates for new conversion technologies, and potential constraints on advanced SAF production due to feedstock availability.

The report also focused on identifying barriers to providing sustainable quantities of feedstocks, such as a lack of biomass production capacity and high relative costs of production, recovery, and transportation for feedstocks.

This analysis considered the entire lifecycle from feedstocks, including MSW, FOGs and others, to fuel, including SAF and co-products



Source: ICF Analysis

2 Summary

Feedstock opportunity

This report details an in-depth analysis to determine the availability of feedstocks for SAF production in Japan. The assessment concluded that woody biomass, municipal solid waste (MSW), and Power-to-Liquid (PtL) feedstocks (including renewable energy, hydrogen, and waste CO2) are the most scalable options for domestic SAF production in Japan. While there's some availability of used cooking oil (UCO) and tallow, their widespread use by other industries limits their availability for SAF production. Novel feedstock sources, like microalgae-derived feedstocks, may be important over the long term but require considerable technology development to be commercially viable.

Table 1: Feedstock opportunity for Japan

Category	Feedstock	Availability Criteria			Overall potential in Japan
		Technically Available	Sustainably Available	Allocation to Aviation	
Waste fat, oil and grease (FOG)	Used cooking oil (UCO)	High	High	Low	Medium
	Animal waste fat (tallow)	High	Medium	Low	Medium
Lignocellulosic and biowaste	Municipal Solid Waste (MSW)	High	High	Medium	High
	Agricultural residues	High	Medium	Medium	Medium
	Woody biomass	High	High	Medium	High
Power-to-Liquids	CO2 and Hydrogen	High	High	High	High
Novel feedstocks	Algae	Low	Low	Low	Low

Legend	
High	green
Medium	amber
Low	red

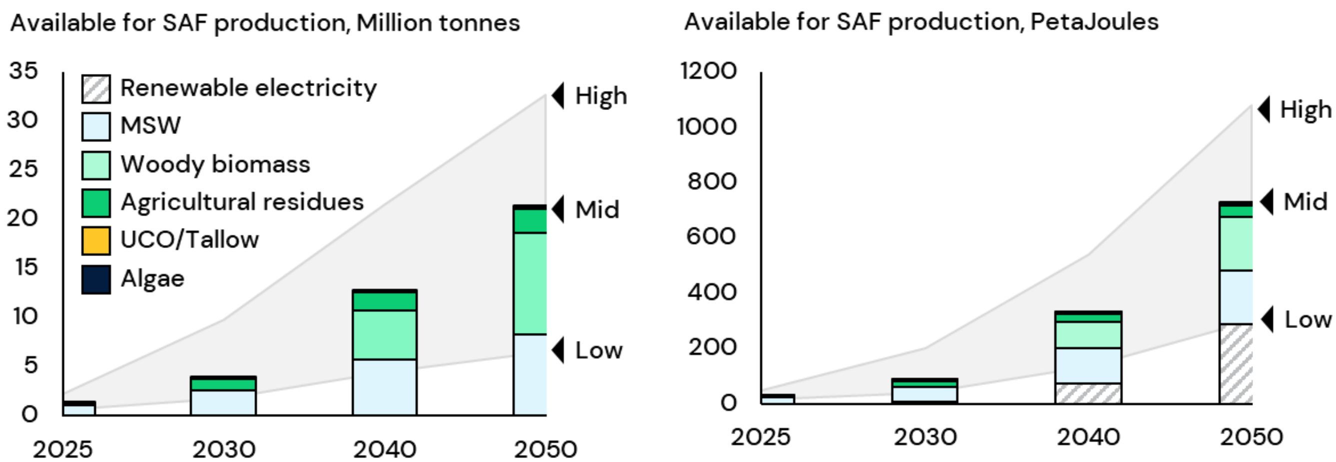
ICF analysed biogenic feedstocks in tonnes to provide a basis for comparison. However, this comparison tends to understate the contribution from feedstocks such as UCOs and tallows due to a difference in energy density. Higher energy density can enable much higher yields of SAF production. Additionally, non-biogenic feedstocks such as renewable electricity cannot be measured in tonnes. To enhance accuracy, the volume of feedstocks was converted into energy in terms of petajoules (x10^{15} Joules), to provide a more effective metric.

Taking these considerations into account, ICF assessed the overall availability of feedstocks for each of the three previously outlined scenarios. The comprehensive evaluation reveals the total availability of feedstocks in Japan as follows:

- The **low scenario** estimates that 40 PJ in 2030 and 299 PJ in 2050 of biological and non-biological feedstocks are available to be allocated to aviation.
- The **mid scenario** estimates that 85 PJ in 2030 and 726 PJ in 2050 of biological and non-biological feedstocks are available to be allocated to aviation.
- The **high scenario** estimates that 201 PJ in 2030, and 1079 PJ in 2050 of biological and non-biological feedstocks are available to be allocated to aviation.

In the high scenario, it is observed that the availability of feedstocks can significantly increase with the right support mechanisms in place. However, it is crucial to acknowledge the varying levels of technology readiness among the different feedstocks. The HEFA process for UCO and tallow has reached a higher level of maturity compared to the FT process required for MSW and the AtJ process necessary for woody biomass and agricultural residues. Understanding these differences is pivotal in assessing the feasibility and scalability of alternative aviation fuels derived from diverse feedstocks.

Feedstock availability can reach up to 725 PetaJoules per year by 2050 if supply chain developments for feedstocks are supported



Source: ICF analysis, negligible amounts of novel feedstocks, UCO, and tallow are not visible on graph

The findings showcase varying levels of opportunity for feedstocks in Japan. Notably, there are sufficient feedstocks, including MSW and renewable electricity, that exhibit the potential for significant carbon intensity emissions reduction. However, realising the rapid development scenario potential of these feedstocks requires support. This support is crucial for developing new supply chains, and for mitigating risks associated with these technologies and facilitating widespread production. While there is an opportunity for HEFA, particularly with a substantial volume exported, the analysis suggests even greater potential for other feedstocks. Therefore, fostering the necessary support mechanisms is essential to unlock the full potential of advanced feedstocks.

Feedstock availability by prefecture

Most feedstocks are only economical when the transport costs and emissions are minimized by refining into higher-value intermediaries or finished products close to the point of collection. Therefore, the local availability of feedstocks will determine the infrastructure required in each region. To determine the feasibility of SAF facilities in Japan, ICF conducted an analysis utilising the Geographical Information Systems (GIS) software to map the distribution of SAF feedstocks based on forest and agricultural area, as well as population distribution by prefecture. The resulting distribution of these critical areas was then weighted against the energy availability in petajoules of each feedstock, providing a nuanced overview of feedstock availability across different locations in Japan.

According to this analysis, Hokkaido accounts for 90% of cultivated land in Japan resulting in the highest availability of agricultural residues and woody biomass. Additionally, the Tokyo metropolitan area and its surrounding prefectures result in the highest availability of UCO and MSW attributed to elevated population density compared to other prefectures.

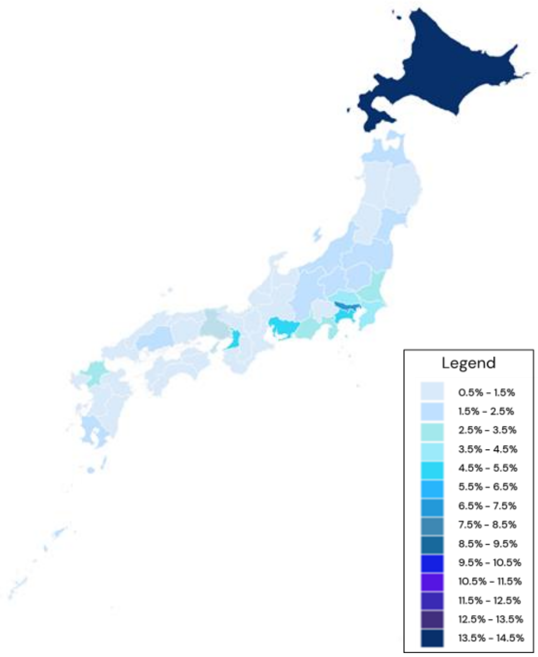
This analysis further analysed renewable energy availability by energy source, as well as existing refineries and their respective refining capacity by prefecture. Providing an understanding of the existing refining infrastructure will outline the opportunity for co-processing locations, which is the process of simultaneously processing HEFA-feedstocks with petroleum feedstocks in existing refinery infrastructure. SAF production additionally offers the opportunity to sustain existing refining infrastructure and jobs by converting decommissioned fossil fuel refineries to renewable fuel facilities.

The demand for fossil fuels in Japan is expected to decrease due to the country's efforts to reduce its dependency on imported fossil fuels, address climate change, and increase the use of renewable energy sources. The anticipated decline in demand for oil products in Japan is projected to reach 7.1% from fiscal year 2021 to 2026.[22] This trend is echoing throughout the oil industry, exemplified by ENEOS' decision to cease operations at its Wakayama facility (120,000 barrels per day), and Idemitsu's announcement to close its Yamaguchi facility (120,000 barrels per day), slated for 2024[23]. Moreover, ENEOS foresees a significant 50% reduction in domestic fuel consumption by the year 2040[24].

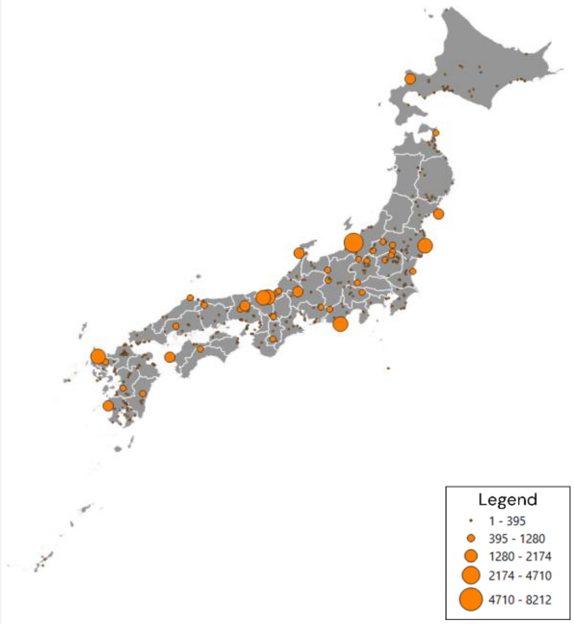
Examples of this have been occurring across the EU and the US. The Grandpuits refinery, one of the oldest refineries in France, is to be converted into a zero-crude facility to support the development of fossil fuel substitutes in support of the country's goal of carbon neutrality. The facility will produce 170,000 tonnes of SAF per year and create up to 1,000 jobs.[25] Another example includes the Phillips 66 refinery in Rodeo, California, which is being converted into a renewable fuels facility and is expected to produce over 800 million gallons of renewable fuels per year. The following page will provide an overview of feedstock, renewable energy, and refining capacity distribution across Japan.

[22] Japan's Top Refiner Eneos Is Gearing Up for the Oil Industry's Decline - Bloomberg
[23] Country Analysis Brief: Japan (eia.gov)
[24] Japan's Top Refiner Eneos Is Gearing Up for the Oil Industry's Decline - Bloomberg
[25] Grandpuits Refinery Conversion, Seine-et-Marne, France (nsenergybusiness.com)

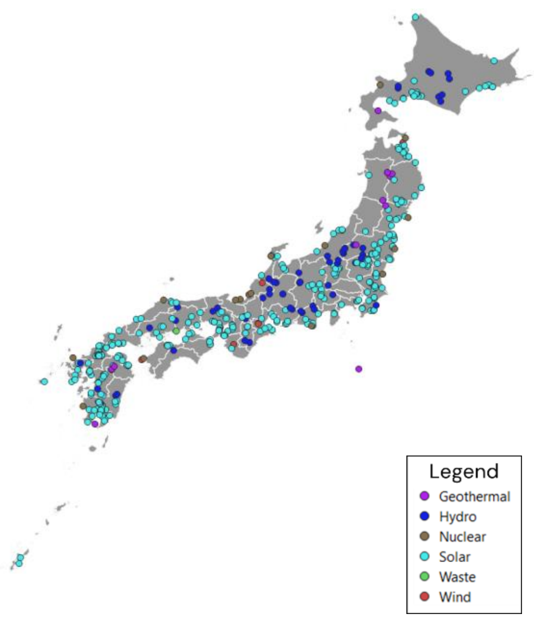
Total feedstock[1] production by prefecture



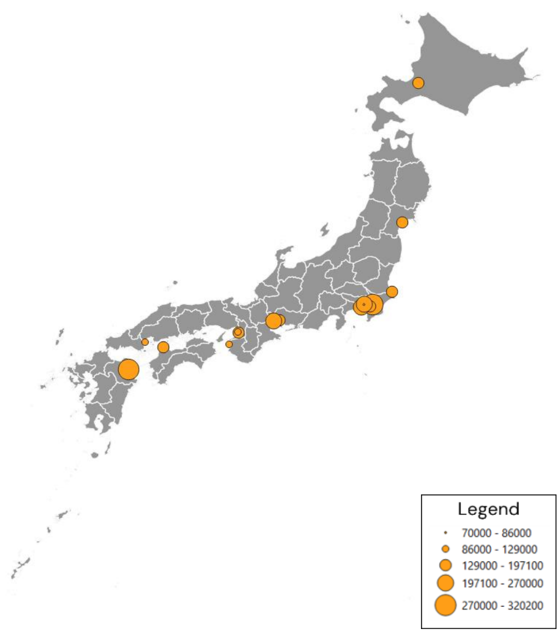
Distribution of renewable energy generation (megawatts)



Distribution of renewable energy by energy source



Distribution of existing refineries by refining capacity (barrels per day)



Source: ICF Analysis, QGIS Software

[1]Note: Feedstocks included are woody biomass, agricultural residues, MSW, FOGs, and renewable electricity

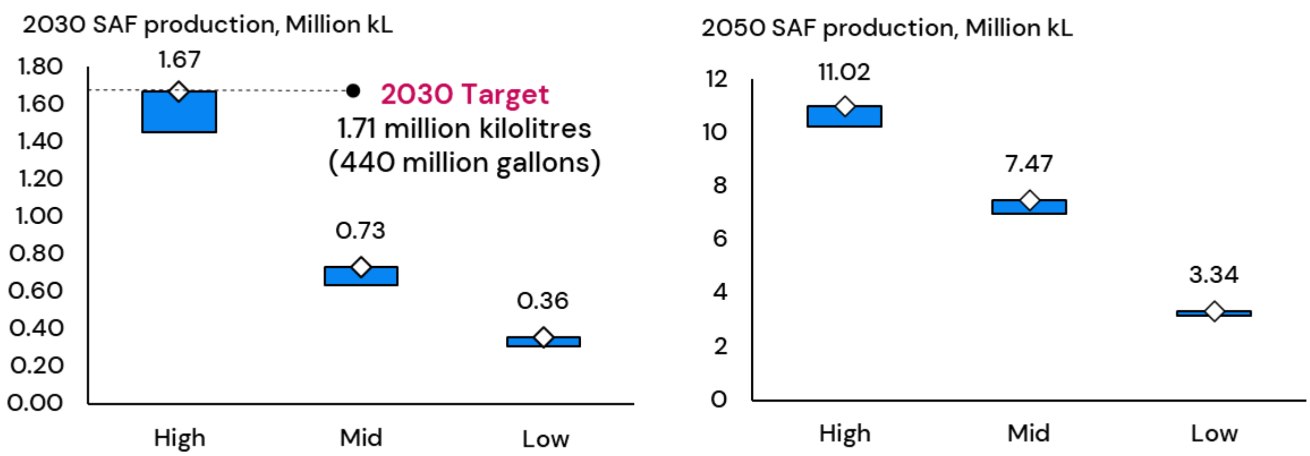
Estimated SAF production

Utilizing the domestic feedstock availability, based on technical availability, sustainable availability, and allocation to aviation, ICF determined the potential volume of SAF production in Japan. This was determined for each of the previously outlined scenarios:

- The **low-scenario** estimates that available feedstocks would be sufficient for approximately 0.3 million kiloliters (95 million gallons) of SAF in 2030 and 3.3 million kiloliters (883 million gallons) of SAF in 2050.
- The **mid-scenario** estimates that available feedstocks would be sufficient for approximately 0.7 million kiloliters (193 million gallons) by 2030 and 7.5 million kiloliters (1975 million gallons) by 2050.
- The **high-scenario** estimates that available feedstocks would be sufficient for approximately 1.67 million kiloliters (441 million gallons) by 2030 and 11 million kiloliters (2911 million gallons) by 2050.

In the short term (2030), only the high-scenario achieves a theoretical volume close to the 10% SAF target (1.71 million kiloliters) with domestic feedstocks. This is contingent upon the implementation of favourable policy mechanisms that prioritize SAF production over renewable diesel and naphtha and facilitate the development of robust supply chains for feedstock.

Domestic feedstock production, assuming mandates in place favouring SAF production over RD and Naphtha, can reach up to 1.67 million kiloliters

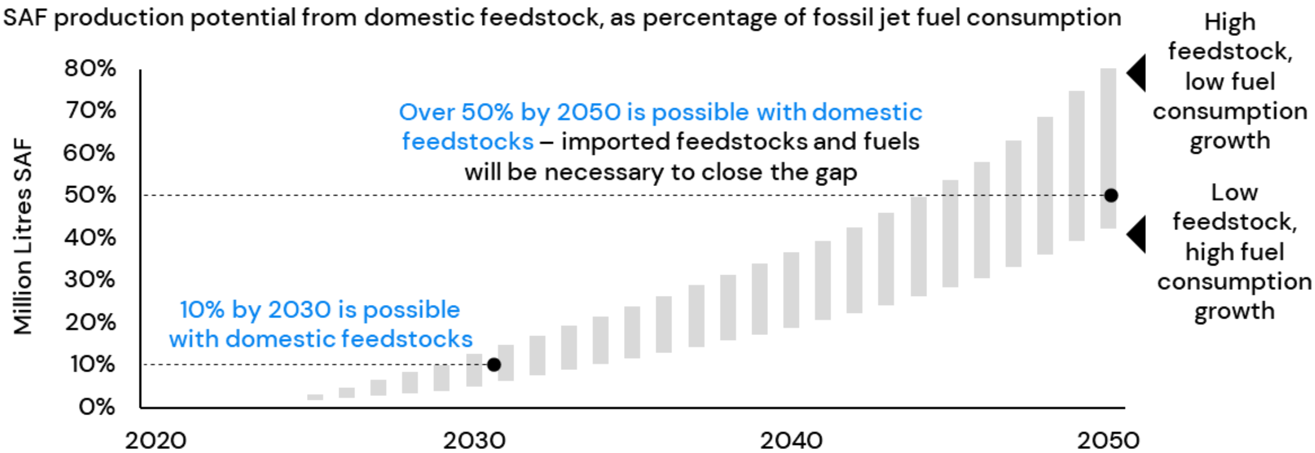


Source: ICF Analysis

In the long term (2050), over 80% of jet fuel demand could be met with domestic feedstocks. Domestic feedstock availability is driven by advanced feedstocks, such as MSW and renewable electricity. These feedstocks have the added benefit of a low carbon intensity, providing the opportunity for high emissions reduction. This is favourable for achieving the country's decarbonisation goals. While these feedstocks have the potential for a high emissions reduction, the technologies to convert these feedstocks have not yet been developed at a commercial scale. Therefore, while domestic feedstock availability will only limit growth in the medium to long term, refining capacity is expected to constrain production in the short term.

Refining capacity is the immediate constraint, with feedstock only limiting growth in the mid to long-term

SAF production potential from domestic feedstock, as percentage of fossil jet fuel consumption



Source: ICF analysis

To utilize a majority of the feedstocks available in Japan, several factors have to be achieved. These include the development of supply chains, and new facilities, and the technology must first develop and de-risk. Therefore, significant investment will be required to achieve large-scale production capacity and stable supply by 2050. While economic viability is key to scaling the SAF industry, the following factors constrain the deployment rate:

- **Limited organizational capacity:** The SAF industry (at a global scale) is currently small, and few organizations have developed the capacity and knowledge to build SAF facilities. The industry will grow as these organizations increase in capacity, as additional start-ups enter the market, and as organizations in related markets pivot to SAF production. The market will take several years to develop, limiting the rate of deployment, specifically for SAF production using advanced feedstocks.

- **Permitting constraints:** Environmental permitting can take several years, as may the certification to sell fuel into the policy schemes.

- **Physical bottlenecks:** This includes limitations on technical components, such as catalysts and reactors, as well as building materials such as concrete and steel.

- **Technology development and risk:** Some technologies have only been proven on a limited scale and/or duration. As the most mature technology, the HEFA pathway is the most widely used today. The AtJ and FT pathways, which support the conversion of advanced feedstocks are currently undergoing commercial deployment. Producers and capital providers will wait until a technology has reached a higher technology readiness level (TRL) before constructing and funding new facilities.

While there are existing initiatives and funding mechanisms, substantial funding, complemented by domestic policies to reduce both capital and operational costs of SAF production, will be required to establish and expand SAF production facilities. Additionally, government targets to increase the use of SAF, such as the introduction of a SAF target by METI and NEDO in Japan, emphasize the need for substantial funding.

Estimated production of co-products

Every renewable fuel facility will produce a mixture of products, typically including renewable diesel, SAF, naphtha, and potentially other fuels. Renewable diesel is a lower-carbon, renewable-based alternative to petroleum-based diesel and can be a drop-in replacement for ultra-low sulfur diesel. Similarly, renewable naphtha is a drop-in replacement for traditional naphtha, which can be used as raw material in the chemical industry.

The production of domestic SAF diverts feedstocks from existing uses, such as biofuel production. This presents an opportunity for the co-products to be reallocated to these industries, such as the use of renewable diesel for the production of biofuels and chemicals. This reallocation has the potential to result in added benefits, such as supporting refiners, petrochemical companies, and hydrogen producers in meeting their sustainability targets and reducing carbon emissions.

The increasing capacity for renewable diesel production and the role of renewable naphtha in decarbonization efforts highlight the growing importance of these co-products in the transition to more sustainable fuel sources. This analysis determined the production of co-products in relation to domestic SAF production for each scenario, which are as follows:

- The **low-scenario** estimates that available feedstocks would support renewable diesel production of 0.1 million kilolitres (22 million gallons) by 2030 and 0.7 million kilolitres (191 million gallons) by 2050, as well as naphtha production of 0.1 million kilolitres (17 million gallons) by 2030 and 0.7 million kilolitres (181 million gallons) by 2050.

- The **mid-scenario** estimates that available feedstocks would support renewable diesel production of 0.2 million kilolitres (42 million gallons) by 2030 and 1.6 million kilolitres (425 million gallons) by 2050, as well as naphtha production of 0.1 million kilolitres (35 million gallons) by 2030 and 1.5 million kilolitres (410 million gallons) by 2050.

- The **high-scenario** estimates that available feedstocks would support renewable diesel production of 0.4 million kilolitres (95 million gallons) by 2030 and 2.4 million kilolitres (627 million gallons) by 2050, as well as naphtha production of 0.3 million kilolitres (85 million gallons) by 2030 and 2.3 million kilolitres (604 million gallons) by 2050.

It is important to note that the renewable fuels industry is shaped by various elements, including government policies, market demand, and feedstock supply, all of which can impact profitability and growth. These factors were considered in the development of feedstock diversion scenarios for the domestic production of SAF, as outlined in the following analysis.

Comparison of results to existing studies

The analysis incorporates findings and insights from existing studies that have been conducted on a global scale, within specific regions, and at the country level. At the country level, this analysis builds on and validates the research conducted by UCO Japan, METI, and most notably the study conducted by the Japan Transport and Tourism Research Institute (JTTRI)[26], and the "Assessment of bioenergy potential and associated costs in Japan for the 21st Century", by Wu et al, published in Renewable Energy Volume 162 in December 2020[27].

Utilising a similar methodology to the JTTRI study, ICF determined the availability of each feedstock and converted it to energy to enhance the comparison capability between feedstocks. Based on this analysis, advanced feedstocks, such as woody biomass, MSW, and renewable electricity, offer the highest opportunity for SAF production in Japan. The JTTRI analysis outlines a similar result, aside from the utilization of renewable energy. The ICF analysis estimates SAF production to range between 3.34 million kiloliters to 11 million kiloliters by 2050. The JTTRI analysis estimates SAF production from domestic feedstocks to range between 7.06 million kiloliters and 13.13 million kiloliters.

The study conducted by Wu et al estimates domestic feedstocks to contribute 3,430 PJ to 3,780 PJ in total domestic technical bioenergy in the 21st century. While ICF estimates a significantly lower contribution at 1100 PJ by 2050, a similar methodology was utilized outlining the challenges in demand from power generation and the development of the domestic supply chain.

The integration of findings from these various studies not only enriches the analysis but also underscores the complexities and opportunities inherent in the bioenergy and SAF production landscape. This multifaceted approach is essential for informing strategic decision-making and policy development in the pursuit of a SAF ecosystem.

26 R01_MRI2021_A4縦_報告書_日本語版 (jttri.or.jp)
27 Assessment of bioenergy potential and associated costs in Japan for the 21st century - ScienceDirect

3 Feedstock analysis

This section evaluates the feedstock groups in detail. In order, the following have been considered:

- Waste fats, oils, and greases (FOGs)
- Municipal solid waste (MSW)
- Agricultural residues
- Woody Biomass
- Novel biogenic feedstocks (e.g. Algae)
- Power to liquid (including renewable electricity and recycled Carbon)

Waste fats, oils, and greases (FOGs)

1. Feedstock Description

Waste fats, oils, and greases include used cooking oil (UCO), and waste animal fats (tallows). Used cooking oil (UCO), commonly referred to as waste cooking oil, refers to oil that has been previously used for cooking, frying or food production. UCOs are typically collected from restaurants, households, and the food industry. Proper management of UCO diverts the insoluble fats and greases away from landfills and municipal water systems, reducing environmental impacts, blockages, and contamination risks.

Animal waste fat, or tallow, is a rendered form of animal fat sourced from livestock such as cattle, pigs, and poultry. Rendering refers to a process through which fats are extracted, which helps maximize the utilisation of animal resources while minimizing waste, making it an essential aspect of sustainable resource management within the meat industry.

Collected and processed, both UCOs and tallows are commonly used in industries including the production of raw materials, animal feed, and biofuels. The collection and use of UCO varies greatly by country, particularly driven by regulation. UCO is a valuable feedstock for SAF production as it is considered a low-carbon feedstock that is both technologically mature and commercially available. However, global volumes are relatively constrained, with global UCO production limited by the use of food, only a fraction of which is collected and reused[28]. Tallows are similarly constrained by the size of the meat industry.

2. Methodology

As different factors drive their production, the supply of UCO and Tallows was analysed separately. To understand the current and potential volume of UCO that can be collected and used in Japan, the following analysis was conducted:

[28] Indika Thushari, Sandhya Babel, Comparative study of the environmental impacts of used cooking oil valorization options in Thailand, Journal of Environmental Management, Volume 310, 2022, 114810, ISSN 0301-4797, https://doi.org/10.1016/j.jenvman.2022.114810

1. Analysis of total UCO production.
2. Analysis of current and forecast UCO collection from households, restaurants, and the food industry.
3. Assessment of feedstock utilisation across different industries and development of diversion scenarios.
4. Quantification of the volume available for SAF production.

A similar methodology was used to assess the amount of tallow produced from the livestock available in Japan:

1. Analysis of total tallow production.
2. Analysis of forecast tallow production.
3. Assessment of feedstock utilisation across different industries and development of diversion scenarios.
4. Quantification of volume available for SAF production.

The following sections sequentially assess the current and forecast production, and then analyse the interaction with other industries together. This approach was taken to reflect the different drivers of production, but similar end-use industries.

3. Assessment

Used Cooking Oil (UCO)

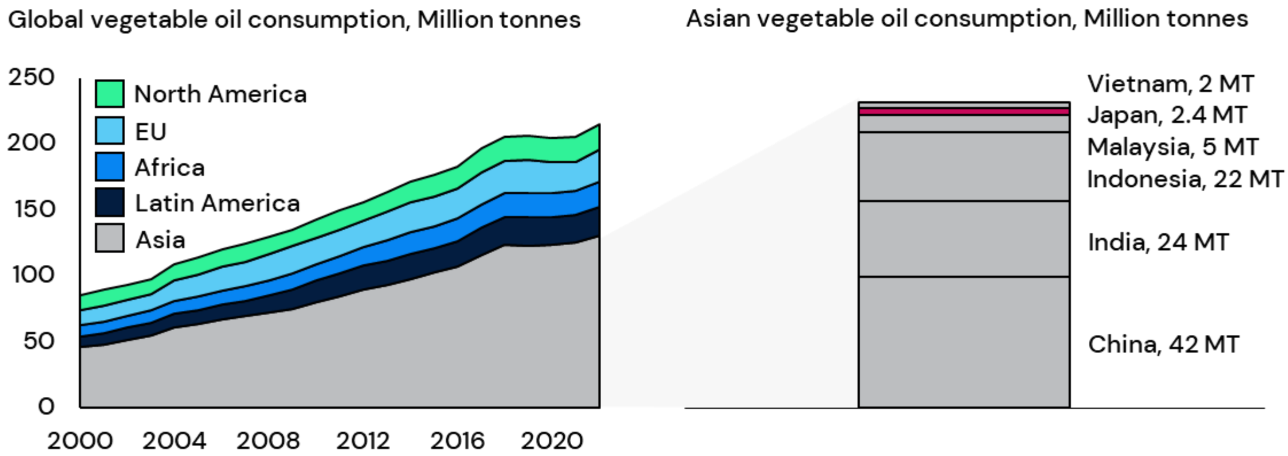
1.1 Analysis of total UCO production

The global annual production of UCO is estimated to be 20-30%[29] of the total vegetable oil consumption per year. According to the OECD, the annual global vegetable consumption reached an estimated 240 million tonnes in 2022[30], with the majority of the consumption in Asian countries.

Most of the consumption in Asia is driven by China with 42 Mt (c. 43%) consumed annually and India with 24 Mt (c. 25%) consumed annually, with Japan contributing only 2.4 Mt (c. 2%). The differences in production are predominantly driven by population numbers, with economic strength and culinary preferences as secondary factors.

[30] https://stats.oecd.org/viewhtml.aspx?datasetcode=HIGH_AGLINK_2021&lang=en#

Global vegetable oil consumption reached 240 MT in 2022 with Japan's consumption reaching up to 2.4 MT to total consumption in Asia



Source: OECD-FAO Agricultural Outlook 2022-2031

Based on the global annual production rate, the total amount of vegetable oil consumption in Japan is estimated to produce about 480-730 kilotonnes of UCO in 2022.

1.2 Analysis of current and forecast UCO collection from households, restaurants, and the food industry

In Japan, once used, vegetable or cooking oil is considered waste and collected free of charge by licensed companies under the Japanese Waste Management and Public Cleansing Law.[31] This law was enacted in 1970 to preserve the living environment and improve public health through the restriction of waste discharge, appropriate sorting, storage, collection, transport, recycling, disposal, or the like of waste and conservation of a clean living environment.

However, a significant portion of UCO is improperly disposed of each year, due to set behaviours compounded by the absence of suitable regulations and effective enforcement. A study conducted by the ICCT suggested that the current collection rates in Japan are relatively low, with household collection rates estimated at 3-5%, and those of restaurants and the food industry range from 20-40% and 40-50% respectively. collection from restaurants is typically much higher as it's more affordable to collect from the larger point sources, while households generate much less per house, so the collection is typically more expensive and consequently lower.

The study draws upon collection rates reported by the city of Kyoto. Kyoto has an established UCO recycling infrastructure to support the production of biodiesel to fuel city-owned vehicles, such as buses and garbage trucks. Kyoto's household collection rate is reported at 13%, representing the highest figure among Japanese cities. The collection of UCO in Kyoto is carried out in partnership with citizens, with the cooperation of the "Regional Waste Reduction Promotion Council" formed in each region to support the cooperation of volunteers.

[31] WASTE MANAGEMENT AND PUBLIC CLEANSING LAW (env.go.jp)

This partnership is conducted voluntarily and is not supported by regulation. To extrapolate this rate across Japan, it was estimated that urban areas across the country with less developed infrastructure achieve a collection rate of 3%-5%, which is slightly less than half of Kyoto's current collection rate. This is in line with many European countries (such as Italy, Portugal, Spain, and Germany), although less than some with well-developed collection systems, suggesting that this is a reasonable estimate when collection incentives are limited but could be improved if required.

To estimate the total amount of UCO produced annually from households, restaurants, and the food industry, ICF used the current collection rates as outlined by the ICCT, and applied the following:

(1) **Households:** The total amount of UCO collected from households in Kyoto was reported to be 13,000 litres in 2022[32], equivalent to 118,300 Kg per year[33]. This value was then converted to a per capita rate using the current population in Kyoto and multiplied by the total urban population in Japan. As the current collection rate in Kyoto is higher than in other parts of Japan, the total amount of UCO was adjusted to assume an average collection rate across Japanese urban areas of 5%. This gave a total amount of UCO currently collected from households in Japan as 3.6 kilotonnes per year.

(2) **Restaurants:** Using a reported collection in Kyoto of 1.5 million litres annually[34], the volume was converted to a per capita rate in kg using the current population in Kyoto and urban population in Japan and extrapolated by assuming an average collection rate of 40% as outlined by the ICCT study. This gave the total amount of UCO collected from restaurants at 117 kilotonnes per year.

(3) **Food Industry:** Using the total amount of UCO produced in Japan (c. 680 KT, adjusted for urban population only) the amount of UCO produced from households and restaurants was subtracted to determine a remainder of 361 kilotonnes produced by the food industry. Assuming a collection rate of 50%, as outlined by the ICCT study, the total amount of UCO collected from the food industry was estimated at 120 kilotonnes per year.

To estimate the potential increase in collection rates, the collection rates in countries with mature and incentivized collection systems were researched. The government in South Korea offers incentives to enhance the collection rate of UCOs and achieves collection rates of 18.6% for households, 78.6% for restaurants, and 98.6% for the food industry[35]. Analysis by T&E estimates the rate in some European countries to be higher, with household collection rates in Belgium (45%), Sweden (47%), Netherlands (41%), and Austria (34%)[36]. Achieving these high collection rates involves developed infrastructure, incentives, behaviour change, and other factors. As an example, in 2016, Belgium had over 700 collection points, while the Netherlands had 2,000, and both required people to travel and deposit household UCO at these collection points. It is also notable that the highest household collection rates were achieved in relatively small countries with populations of 12m or less, and the collection rate in larger European countries is meaningfully lower in the UK (12%), Germany (2%) and

[32] Kyoto City: Biodiesel Fuel Project
[33] Assuming UCO density of 910 grams per liter
[34] Food Waste Recycling in Japan | Japan for Sustainability (japanfs.org)
[35] Incentives for waste cooking oil collection in South Korea: A contingent valuation approach - ScienceDirect
[36] https://www.transportenvironment.org/wp-content/uploads/2021/07/CE_Delft__200247_UCO_as_biofuel_feedstock_in_EU_FINAL%20-%20v5_0.pdf

Spain (2%), which may suggest that a country with the size and diversity of Japan may struggle to match the higher end of collection rates. This may be somewhat mitigated by the high urbanization rate of Japan (c. 92%), as collection becomes increasingly expensive as households are more spread out, making it more economically viable in the dense urban areas across Japan.

The increasing value for UCO will incentivize higher collection rates, although there is uncertainty on the highest possible rates. A study by the ICCT estimated collection rates could increase up to 50%, 100%, and 100% for households, restaurants, and the food processing industry respectively.
The collection rates were forecast to increase from the current levels as the incentives and market continue to develop. The household collection rates were forecast to increase to 22%, slightly above the rate currently achieved in Kyoto (and South Korea) but conservatively below the rate achieved by some of the smaller EU countries. The restaurant and food industry collection rates were forecast to increase to higher percentages, in line with those achieved in other countries today.

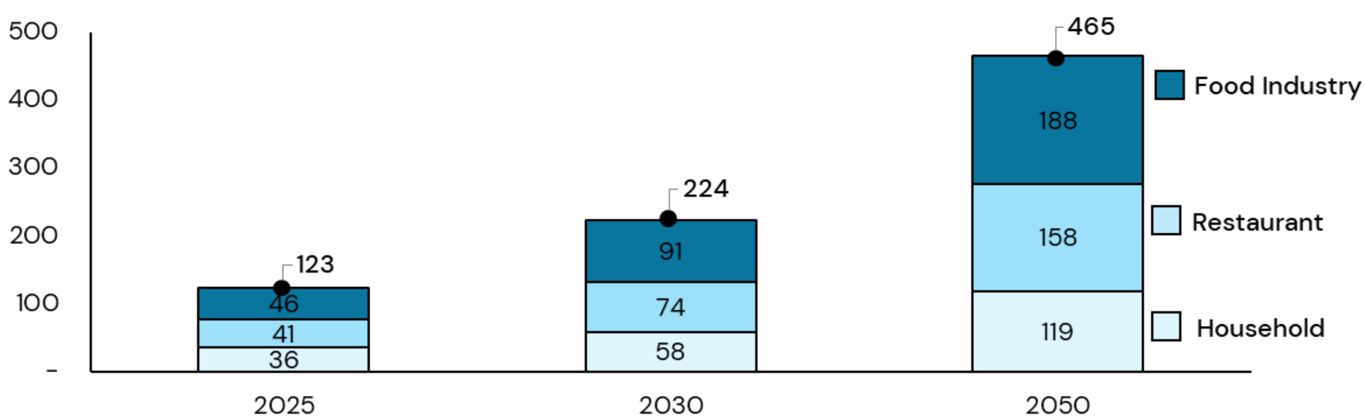
Table 1: Forecast collection rates by category

Category	2025	2030	2050
Household	5%	12.40%	22%
Restaurant	40%	52%	79%
Food Industry	50%	66%	98.6%

Combining the total amount of UCO produced by households, restaurants, and the food industry with these collection rates gave estimates of the potential amount of UCO at 123 Kt in 2025, 224 Kt in 2030, and 465 Kt in 2050.

Forecasted UCO collection rates drive an increase of 123 KT in 2025 to 465 KT in 2050 of UCO from households, restaurants, and the food industry

Central scenario, UCO collection in Japan, kilotonnes per year



Source: ICF analysis

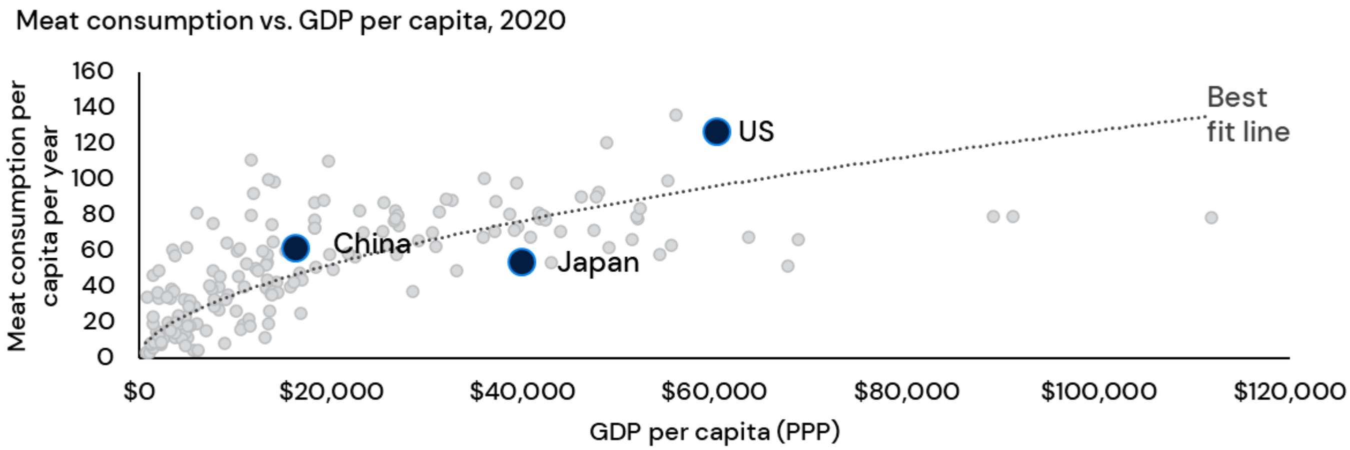
Animal waste fat (Tallows)

1.1 Analysis of current tallow production

Tallow is a by-product of the meat industry, so production is strongly correlated with meat consumption. According to the FAO, the global annual meat production reached 360 million tonnes in 2022, equivalent to an average meat consumption of 120 grams per person per day. Furthermore, there is a positive correlation between income level and meat consumption, and as a result, global meat consumption has increased significantly along with the acceleration of economic growth, increasing from 7 thousand kilograms per capita in 2000 to 9 thousand kilograms per capita in 2020[37].

Meat consumption in Japan has stabilized at slightly above 60 kilograms per capita per year, a notably lower level compared to other countries. This is likely due to the high consumption of seafood as a source of protein in Japan[38], which averaged about 46 kilograms per capita per year in 2020[39].

Japan consumes significantly less meat than other countries with similar per capita GDP (PPP)



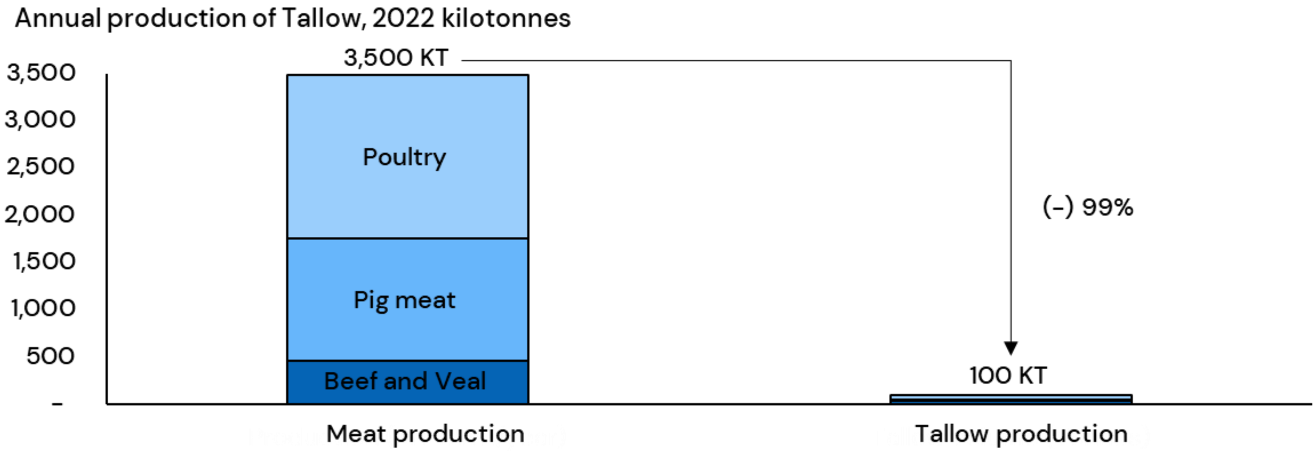
Source: Our World in Data, 2020, https://ourworldindata.org/grapher/meat-consumption-vs-gdp-per-capita?time=latest

Based on the correlation between meat consumption and tallow production, it is assumed that the amount of tallow produced is directly related to the amount of beef and veal, pig meat, and poultry produced annually in Japan. The amount of tallow production per kilogram of beef and veal, pig meat, and poultry was determined based on the carcass weight of each animal multiplied by the percentage of tallow. The values utilised for tallow production were 6.34%, 1.67%, and 2.62% of tallow per kg of beef and veal, pig meat, and poultry respectively. Utilising data published by the United States Department of Agriculture and the Japan Ministry of Agriculture, Forestry and Fisheries, the total volume of meat produced in Japan was estimated to be 3.5 million tonnes in

[37] https://ourworldindata.org/grapher/per-capita-meat-type
[38] https://www.mitsui.com/mgssi/en/report/detail/1221523_10744.html
[39] https://ourworldindata.org/grapher/per-capita-meat-type

2022. This volume is based on 0.4 million tonnes of beef and veal, 1.3 million tonnes of pig meat, and 1.8 million tonnes of poultry meat produced in 2022[40][41].

Total amount of Tallow produced annually in Japan is an estimated 100 KT



Source: ICF analysis

It is important to note that rendered tallows are distinguished between two main types, edible tallow and inedible tallow. Edible tallow (mostly produced from beef and veal) is made exclusively from the highest quality edible fats, and processed for human consumption (e.g. margarine, cooking oil, and baking products) and pet food. Inedible tallows, on the other hand, are processed for livestock feed, oleochemicals, and biofuel production. Edible tallows are further structured into three different categories that are defined according to their risk to human or animal health. Category 1 has the highest risk, Category 2 still offers a high risk, while Category 3 offers the lowest risk and is considered safe for human and animal consumption. For this analysis, it was assumed that a total of 76%[42] of tallows are classified as Category 1 and 2 inedible tallows and can be used for the production of raw materials and biofuels.

1.2 Analysis of forecast tallow production

The FAO projects the number of livestock in Japan to increase through 2030, followed by a slight decrease in 2050. This can be attributed to annual support programs by the Japanese Government to domestic livestock, dairy, and egg producers. In its most recent notification to the World Trade Organization, Japan reported $6 billion in support for beef, pork, dairy, and egg products, accounting for 97 per cent of Japan's total aggregate measurement of support. Additionally, according to the USDA, an estimated 60% of meat consumption in Japan is related to the food industry including tourism. Tourism is expected to continue to increase until 2030 due to the goal of 60 million foreign tourists per year by 2030, as announced by the Japanese government.

[40] DownloadReportByFileName (usda.gov)
[41] This volume is reported in million tonnes CWE – Weight of an animal after slaughter and removal of internal organs skin and head.
[42] Inedible tallow - Big Chemical Encyclopedia (chempedia.info)

The FAO projected increase of livestock (including cattle, pigs and poultry) by 2030 only resulted in an average increase of 1%, whereas the decrease of livestock from 2030 to 2050 resulted in an average decrease of 7%. Based on these assumptions, the total volume of tallow production was adjusted to 100 kilotonnes by 2030, and 92 kilotonnes by 2050.

4. Discussion

Assessment of the feedstock utilisation across different industries and development of diversion scenarios

According to UCO Japan, the total amount of FOGs produced in 2021 was allocated to the production of animal feed (c. 40%), raw materials (c. 10%), and biofuels (c. 2%). The remaining volumes were either exported (c 24%), primarily to European countries and China or unaccounted for due to difficulty in collecting or recycling. It is assumed that each of these allocations can be diverted with supporting government policies and guidelines, as well as economic benefits.

Based on the reported allocation of FOGs, three diversion scenarios were developed: (1) low scenario representing a conservative roll-out of government support, (2) mid scenario representing a median, and (3) high scenario representing an aggressive deployment of government support. These scenarios were built on the following assumptions to determine the amount of FOGs available for the production of SAF.

(1) **Use of exported volumes domestically.** Today, an estimated 24% of FOGs are exported to other countries, primarily for biofuel production. Diverting the exported volumes to be used domestically, presents a strong economic case aligned with the following objectives: (1) energy security, (2) achieving a net-zero economy, and (3) economic growth. Domestic fuel production bolsters energy security, contributing to self-sufficiency, while also supporting supporting Japan's commitment to achieve a net-zero economy by 2050. The production of high-value renewable fuels from low-value waste oils can also drive economic growth.

(2) **Diversion from animal feed production.** The diversion from animal feed production was based on the following three assumptions: (1) the increase in FOG collected allows the percentage used for feed to reduce while the volume remains level, (2) the expected decrease in meat consumption globally and in Japan, and (3) potential changes to feed regulations to promote animal and human safety. The total number of FOGs is expected to increase by 2050 due to increased collection and recycling rates. Therefore, although the allocated percentage for animal feed is decreasing over time, the total amount of FOGs allocated to the industry will remain static with only a slight decrease.

(3) **Diversion and reallocation from biofuel production and industrial use.** Every SAF facility will also produce volumes of renewable diesel and naphtha as by-products. These can be reallocated back to industries for us as biofuels and chemical production. Replacing biodiesel use with renewable diesel is beneficial considering the much higher blend rations that renewable diesel can be used at, and better cold-weather performance. However, this transition must be staged to ensure biodiesel facilities do not become stranded assets, so this transition was assumed to happen over the average 20-year lifespan of biodiesel facilities, with replacement only once the biodiesel assets are retired.

These assumptions were utilised to build the following diversion scenarios estimating the potential percentage of FOGs that can be diverted from each industry to be allocated to the aviation industry.

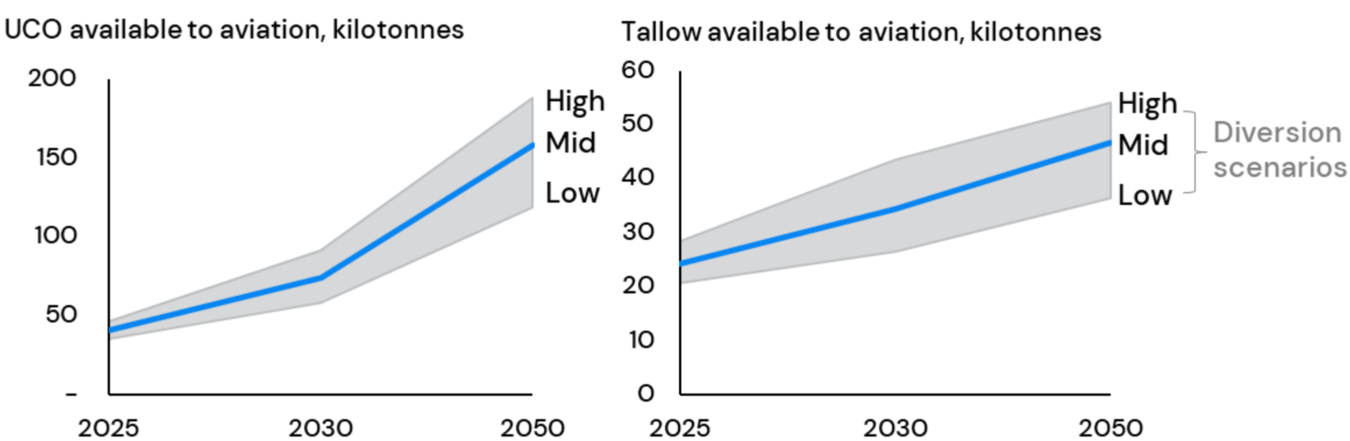
Table 2: Scenarios estimating the potential percentage of UCO and tallow that can be diverted from each industry for SAF production

Allocation	2025		2030		2050	
Animal Feed	Low	5%	Low	15%	Low	30%
	Medium	8%	Medium	30%	Medium	70%
	High	10%	High	50%	High	100%
Industrial Use	Low	20%	Low	50%	Low	100%
	Medium	50%	Medium	80%	Medium	100%
	High	80%	High	100%	High	100%
Export	Low	100%	Low	100%	Low	100%
	Medium	100%	Medium	100%	Medium	100%
	High	100%	High	100%	High	100%
Biofuel Production (non-SAF)	Low	20%	Low	30%	Low	100%
	Medium	30%	Medium	50%	Medium	100%
	High	50%	High	80%	High	100%

Calculating the volume available for SAF production

Based on the three developed scenarios, low, medium, and high, the total amount of FOGs available to the aviation industry was determined to be an estimated 35-43 kilotonnes in 2025, increasing to 119-188 kilotonnes in 2050 for UCO, and 20-36 kilotonnes in 2025 increasing to 28-54 kilotonnes in 2050 of tallow.

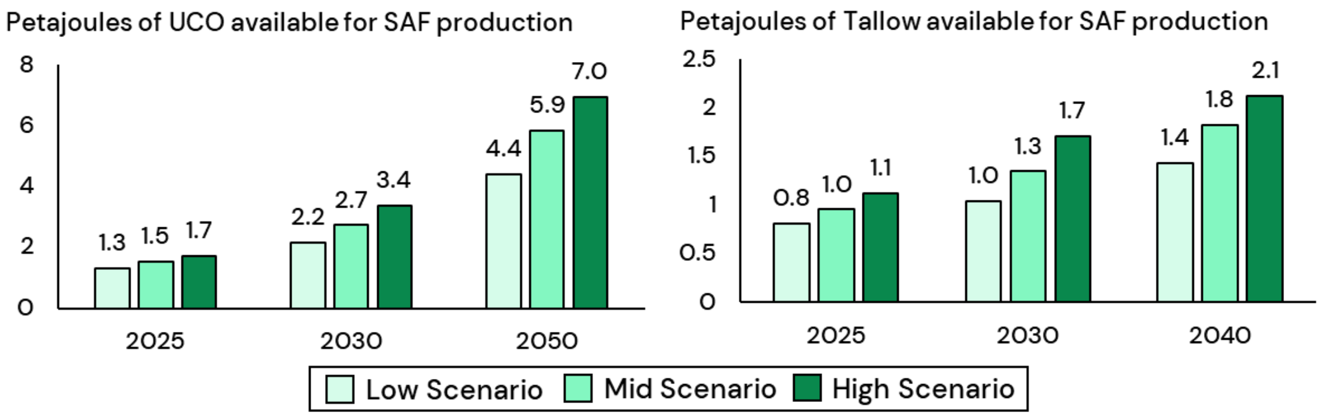
The amount of FOGs available to aviation ranges from c. 35-43 KT in 2025 to c. 119-188 KT in 2050 of UCO, and c. 20-36 KT in 2025 to c. 28-54 KT in 2050 of tallow



Source: ICF analysis

Utilising an assumed energy density of 37 MJ per kg for UCO, and 39.9 MJ per kg for tallow the results were converted into energy to allow for comparison with other feedstocks. Overall, due to an assumed increase in collection and recycling rates for UCO, the total amount of energy available for SAF production is expected to increase to 7.0 PJ by 2050, assuming an aggressive deployment of government support. Tallows, on the other hand, are only expected to yield a total amount of 2.1 PJ of energy available for SAF production by 2050. This difference can be assumed due to an expected decrease by 2050, and an overarching lower production of tallows than UCO.

Forecast of 1.3-1.7 PJ of UCO Energy in 2025 increasing to 4.4-7.0 in 2050, and 0.8-1.1 PJ of Tallow Energy available in 2025, increasing to 1.4-2.1 PJ by 2050



Source: ICF Analysis

Municipal solid waste (MSW)

1. Feedstock Description

Municipal solid waste includes waste products from households and businesses, including paper, cards, wood and greens, plastics, glass, metals, rubber, and other detritus. The World Bank estimated that 2.01 billion tonnes of MSW per year were produced globally in 2016, with extrapolated trends in population and GDP suggesting an increase in production to 3.4 billion tonnes of MSW by 2050[43].

Proper management of MSW is important to reduce greenhouse gas emissions and avoid pollution of water, soil, and land. Unfortunately, a considerable volume of global MSW is mismanaged today, with at least a third dumped or burnt in the open. As a result, there is a global opportunity to produce SAF from municipal waste, improving the management of MSW and supporting the decarbonisation of aviation.

2. Methodology

Japan has a well-developed waste management system, with a complete collection of waste and extensive infrastructure for recycling, reusing, and disposal. The use of MSW for SAF production must integrate within this system, with three areas of opportunity:

[43] https://datatopics.worldbank.org/what-a-waste/

- Replacing existing waste disposal assets as they reach the end of life.
- Management of unrecyclable waste, i.e. to support existing infrastructure
- Diversion of exported waste for domestic use

The size of each opportunity depends on the expected development of the Japanese waste management system. This is assessed in the following sections:

1. Assessment of the legal and regulatory framework guiding the development of the Japanese waste management industry.
2. Analysis of the current and forecast waste production.
3. Analysis of the current waste management and scenario forecast
4. Quantification of the volume available for SAF production.

3. Assessment

Assessment of the legal and regulatory framework guiding the development of the Japanese waste management industry

As Japan experienced sharp economic growth over the twentieth century, the volume of waste increased equally rapidly, from just 6.2 million tonnes in 1955 to 42.2 million tonnes in 1975[44]. This created considerable challenges for Japan, with the linear economy driving very rapid growth in imports and reliance on foreign supply chains, and the severe land constraints limiting the space available to properly dispose of the waste. The *Waste Management Act* was introduced in 1970[45] and laid the foundation for the developing ecosystem by defining categories of waste, the responsibilities of municipalities, and placing considerable obligations to manage industrial waste. This stimulated the construction of the first industrial-scale management facilities, particularly incinerators to reduce the volume of waste. However, continued economic growth and waste production, alongside dwindling landfill capacity, required more stringent regulation.

This regulation was implemented through the *Effective Resource Utilisation Promotion Act* in 1991, and the framework *Basic Act for establishing a sound material-cycle society* in 2000. Together, these defined the 3R approach to drive waste Reduction, Reuse, and Recycling, and created a legal obligation for waste to be managed according to the following hierarchy (1) Reducing generation, (2) Reuse, (3) Recycling, (4) Thermal recovery, and (5) Appropriate disposal. Subsequent acts added additional detail for specific products and defined goals to increase resource productivity, and the recycling rate, and to reduce the final disposal amount. These regulations are crucial to understanding the obligations of MSW, and how updates could be made to reflect the development of new technologies that can allow the use of waste to produce high-value liquid fuels.

Analysis of the current and forecast MSW production

Japanese MSW production grew rapidly during the economic boom, before reaching an apogee of 54.8 million tonnes in 2000. Over the following decades, the low level of economic growth and increasingly stringent waste reduction initiatives reduced the volume of MSW generated to 45 million tonnes in 2010 (-2.7 compound annual

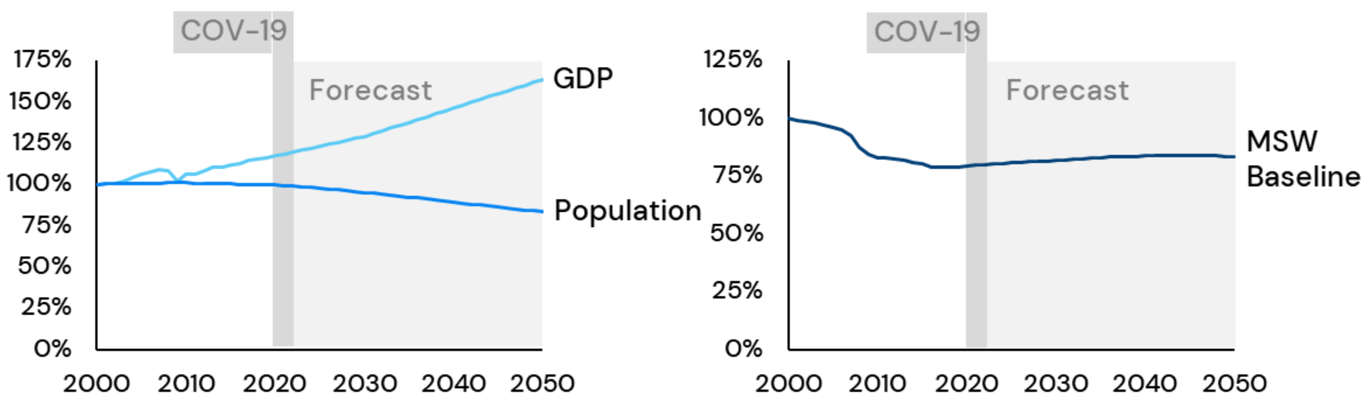
[44] https://www.jwnet.or.jp/assets/pdf/en/20190322133536.pdf
[45] https://www.env.go.jp/content/900453392.pdf

growth rate (CAGR) per year). The reduction continued through 2016, although at a slower rate of -0.8% CAGR as economic growth slightly recovered and some of the easier waste reduction opportunities were saturated.

Three key drivers were used to forecast waste production out to 2050, including (1) population changes, (2) economic growth, and (3) waste avoidance. The OECD forecasts a gradual decline in population numbers, from a peak of 128 million in 2010 to 125 million in 2023 and 106 million in 2050, with the decline in population decreasing waste generation. This reduction is slightly offset by economic growth, which is typically positively correlated to waste generation. However, this has a limited impact as the relationship tapers to a plateau at high levels, so while the OECD forecast[46] GDP growth in Japan of 41% between 2019 and 2050 (c. 1% CAGR), ICF estimates that the net impact will be a gradual growth in baseline MSW generated from 43.2 million tonnes in 2016 to 44.1 Mt in 2023, and 45.8 Mt in 2050.

ICF forecast static baseline MSW generation, with GDP growth offsetting the gradual decline in population

Comparison of Japanese GDP (PPP), Population, and Baseline MSW historical and forecast to 2000



Source: GDP and Population forecasts from the OECD. Historical MSW data from the Japanese Industrial Waste Information Centre. Correlations to forecast MSW developed by ICF. COVID-19 impact is excluded due to the limited impact on waste generation
Note: The MSW Baseline represents the volume before any waste reduction initiatives are implemented.

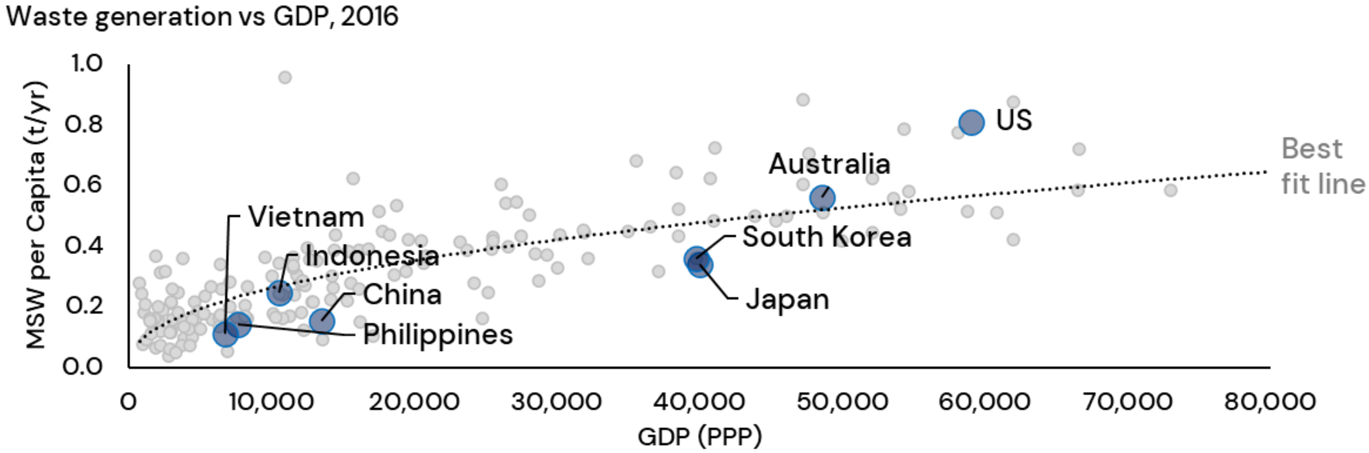
A key factor will be the reduction in waste below this baseline that Japan can achieve. The regulatory framework is supportive of waste reduction, with the 3R framework establishing this as a key priority. The continuous evolution of policies further reinforces this development, for example with the Act on the Promotion of Resource Circulation for Plastics[47] (2022) placing a reduction in single-use plastics as a priority. Alongside these policy initiatives, the potential reduction was evaluated by comparing Japanese waste generation to other countries, and by considering the historical progress.

Comparing Japan to other countries shows that waste generation is already lower than peers. Waste generation shows a strong correlation to GDP in purchasing power parity, with a power relationship representing the best

[46] https://data.oecd.org/gdp/real-gdp-long-term-forecast.htm
[47] https://www.env.go.jp/en/focus/jeq/issue/vol29/The%20Plastic%20Resource%20Circulation%20Act_0128%20final.pdf

fit. This analysis would predict an MSW generation of 0.47 tonnes per capita per year, compared to the 0.34 t/capita/yr reported in 2016. This might suggest that many of the easier opportunities for waste reduction have already been addressed, increasing the effort required to continue and accelerate the pace of waste reduction.

Japan generates significantly less waste than countries with a similar GDP (PPP)



Source: MSW data from The World Bank What a Waste 2.0, 2016 https://datatopics.worldbank.org/what-a-waste/. GDP data in Purchasing Power Parity, from the OECD

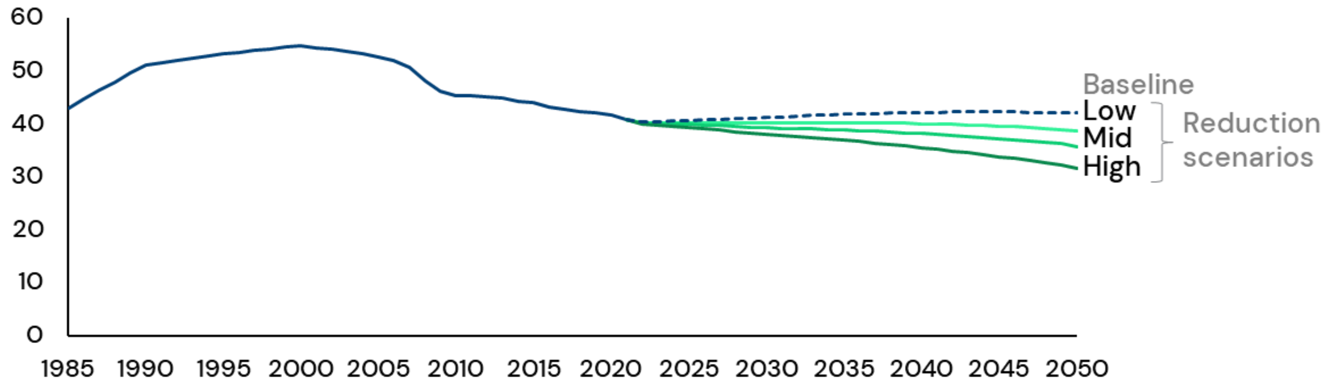
The historical trend shows considerable success in reducing MSW generation, with a steady decrease from the peak in 2000. However, the pace of reduction has slowed from -2.7% CAGR between 2000 and 2010 to -0.8% CAGR through 2016, and -0.6% through 2023[48]. COVID has likely slowed efforts to reduce waste due to the disruption and considerable disposable equipment needed and will have disrupted the accounting as the number of foreign citizens and visitors will have significantly dropped. However, this historical trend suggests a gradual but sustained decrease in MSW generated.

Considering these trends, three scenarios were developed to represent the spread of potential outcomes. These were calculated based on the reduction in 2050 emissions below the baseline, with the low scenario representing an 8% reduction, the mid scenario a 20% reduction, and the high scenario representing a 30% reduction. These are equal to annual reductions of -0.2%, -0.5%, and -0.9% respectively, and therefore match outcomes ranging from a slight slowdown to a slight acceleration in waste reduction efforts.

48 https://www.env.go.jp/en/press/press_01276.html

Three scenarios assess a reduction from c. 41 mt in 2020 to 39-32 mt in 2050

ICF forecast of MSW generation in Japan, Million tonnes per year

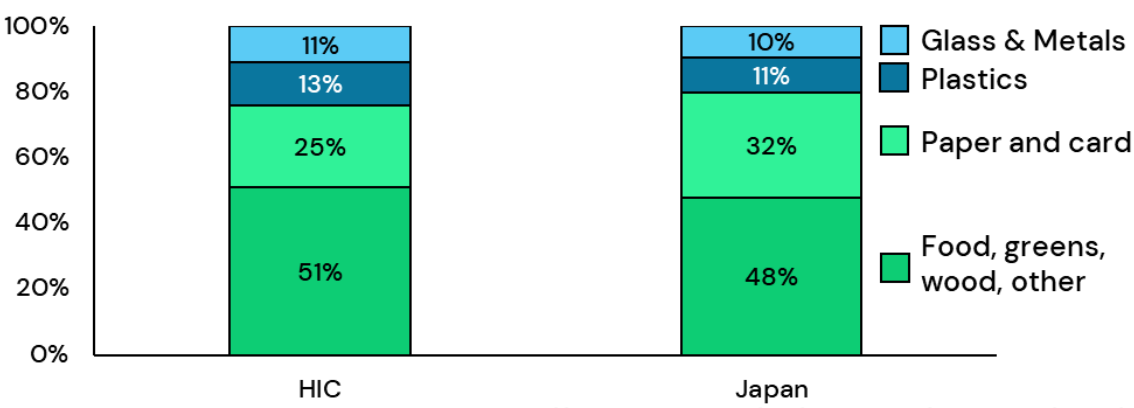


Source: ICF Analysis

Approximately 41 million tonnes of MSW were generated in Japan in 2022, including 29.8 million tonnes of biogenic waste (food, green, wood, paper, card), and 11.2 million tonnes of non-biogenic waste (plastics, glass, metal, and others). This is relatively similar to the average for other high-income countries, as calculated by ICF from data from the World Bank, although with a slightly elevated portion of paper and card. This composition is crucial for the emissions reduction of any SAF produced from this MSW, as the biogenic portion has significantly lower life-cycle emissions compared to the non-biogenic portion.

The composition of MSW in Japan is similar to other high-income economies, although with a notably high level of paper and card

Comparing waste composition in Japan to the average for High Income Economies (HIC) (2016)



Source: Ministry of the Environment https://www.env.go.jp/en/statistics/contents/2017/E2017_Ch4.pdf, World Bank What a Waste 2.0, 2016

Analysis of the current waste management and scenario forecast

The Japanese waste management infrastructure is extremely efficient at collecting and processing the MSW. In 2021, approximately 20% was recycled, 1% was landfilled with no intermediate treatment, and the remaining 79% was incinerated in one of the 1,056 plants. This infrastructure has been built since the mid-1960s, and key priorities were the sanitary disposal of waste and reducing MSW volume. This is particularly important as Japan has an extreme scarcity of useable land to dispose of any residues, with the Ministry of Environment forecasting that 99.8 million m^3 of landfill volume remains, sufficient for 22.4 years of disposal (from March 2021).

The Japanese waste management framework establishes the following hierarchy for waste management (1) Reducing generation, (2) Reuse, (3) Recycling, (4) Thermal recovery, and (5) Appropriate disposal. This analysis assumes that SAF production would be appropriate in the hierarchy between (3) recycling and (4) Thermal recovery, given the effective chemical recycling of the waste into high-value products. To ensure this analysis represents commercially viable opportunities, the retirement rate for existing thermal recovery facilities is considered to ensure few stranded assets.

This approach requires that any recycled volumes are excluded from the availability analysis. With the introduction of the 3R's framework, recycling and reuse increased in priority, and the recycling rate (calculated as the percentage of final mass recycled vs MSW mass) gradually increased from less than 10% in the 1990s to 17.5% in 2004 and 20.8% in 2010[49]. This rate has plateaued since 2010, remaining at 19.9% in 2021[50]. However, this total figure hides significant variation between different waste streams, with very high recycling rates for paper and metals, lower rates for plastics, and little recycling of food, greens, and other products.

The paper recycling rate is likely close to the maximum. In 2022, 79.5% of paper was recovered and recycled[51], which is close to the theoretical maximum as the residual is mostly either non-recoverable (e.g., sanitary paper) or non-recyclable (e.g., water-resistant paper). As a result, approximately 66% of paper manufacture by volume used recovered paper, split with 34.1% for papers and an astounding 93.7% for paperboard manufacture (paperboard can use a higher portion as recovered paper is less structurally robust, so must be combined with wood pulp in paper to give adequate strength). Because the recovery of paper exceeds the consumption of recovered paper, the excess recovered paper is exported, with over 1.8 million tonnes of recovered paper sent overseas in 2022, and a smaller portion (0.1 Mt) is lost or consumed during the process. This paper could potentially be used as a feedstock for SAF production, although the financial viability will depend on the demand and price for recovered paper.

The plastic recycling rate was 22% in 2019[52] (mechanical and materials recycling), although this includes both domestic recycling and processed recyclable plastics that are exported overseas. This recycling rate has only gradually increased, plateauing over the last decade. The export market was severely disrupted when China banned the imports of recyclable plastic waste in 2018 (Operation National Sword[53]), as c. half of Japan's

49 https://www.jwnet.or.jp/assets/pdf/en/20190322133536.pdf
50 https://www.env.go.jp/en/press/press_01276.html
51 http://www.prpc.or.jp/wp-content/uploads/PAPER-RECYCLING-IN-JAPAN-English.pdf
52 https://hk.boell.org/sites/default/files/2022-05/PlasticAtlasAsia2022_en_WEB_0.pdf
53 https://e360.yale.edu/features/piling-up-how-chinas-ban-on-importing-waste-has-stalled-global-recycling

recycled plastic was exported, and over 70% of these exports were shipped to China. This spurred efforts to handle greater plastic waste domestically, and Japan's export volumes decreased from 1.8 Mt in 2015 to 0.7 Mt in 2019[54]. Consequently, the flat plastics recycling rate over this period represents a slight increase in the volume handled. The majority of non-recycled plastic waste is incinerated with energy recovery, with less than 10% incinerated without energy retrieval or landfilled respectively. Some volume of the plastic currently incinerated (with and without energy recovery) could be used for SAF production, although this use must be managed to avoid stranding the existing assets. The carbon intensity of SAF produced using waste plastics is also relatively high.

Approximately a tenth of waste in Japan is metals and glass. This represents no opportunity for SAF production as the material is unusable. Similarly, metals and glass cannot be incinerated, and their high value has supported high recycling rates, with 93% of steel cans recycled, 77% of aluminium cans, and 95% of glass bottles (2015)[55]. The recycling rate for other materials is relatively low. There has been a gradual build-out of composting facilities to manage green waste, with 3.4 Mt of capacity in operation by 2015 (note these facilities also handle a portion of non-municipal waste). ICF estimates that this capacity represents a recycling rate of c. 6% for the total food, green, wood, and other MSW categories[56].

Combining these values (multiplying the recycling percentages for each waste stream by their percentage of MSW) suggests a significantly higher recycling rate than recorded by the government, at 34% in 2021 (vs the government-reported figure of 19.9%). This discrepancy is because the recycling percentages for each waste stream are often calculated on the input volume (e.g. the mass of MSW entering a composting facility), while the mass of processed weight is often significantly less; for example, a composting facility produces 0.75 kg of compost per 1 kg input, with much of the difference lost to the atmosphere. Other facilities, such as paper or plastic recycling will also have a portion of unusable residues which reduces the weight of recycled products compared to the weight entering the facility. The Japanese government calculates the recycling rate based on the final mass of recycled products compared to the MSW generated; as these calculations show, the mass that is managed via a recycling facility is significantly higher. To illustrate the opportunity for SAF production, this analysis will show the MSW mass that is 'input' to recycling facilities as 'recycled', on the basis that the mass lost during recycling is unlikely to be available for SAF production. As a result of this calculation approach, the percentage shown as recycled exceeds the official net statistics.

The values have been established to show a spread of future recycling scenarios, with the low scenario representing a conservative roll-out, and the high scenario representing an aggressive deployment of recycling technologies. The values are calculated as the percentage of each MSW category that is input to a recycling facility, in 2050. Percentages are used rather than absolute values as many of the difficulties with recycling stem from the heterogeneous nature of MSW rather than volume. This assumption can result in a decreasing volume of material recycled even as recycling percentages increase, due to the decreasing total volume of MSW generated.

54 https://coMtradeplus.un.org/

55 https://www.env.go.jp/en/statistics/contents/2017/E2017_Ch4.pdf

56 The composting capacity is c. 15% of all recycling capacity. With a headline recycling rate of 20% this represents 3% of total waste. As Food, Greens, Wood, Other is 48% of total waste, this suggests that (3%/48% = 6.3%) of this category is composted.

Table 1: Current and forecast recycling rates for each municipal waste category

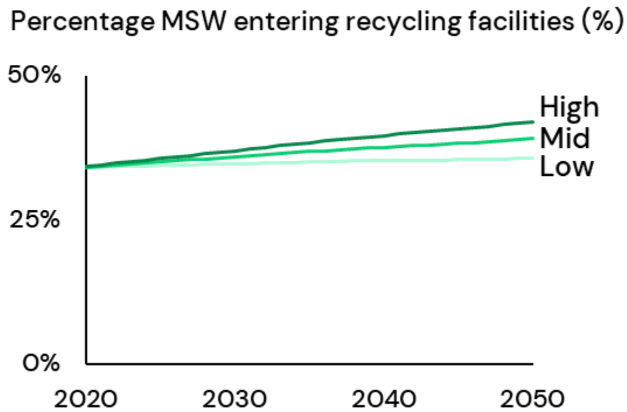
Waste category	Current	Low	Mid	High
	2021	2050	2050	2050
Paper and card	66%	70%	75%	80%
Food, Green, Wood	3%	5%	8%	10%
Plastics	22%	25%	30%	35%
Glass and Metal	90%	90%	90%	90%
Others	1%	2%	3%	5%

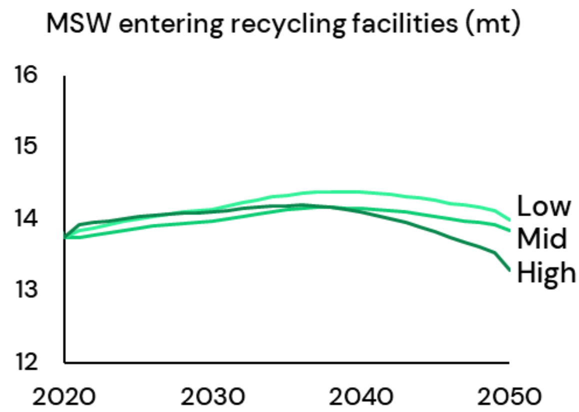
The paper and card percentages are set at the percentage of recovered paper that is consumed, with most of the remainder exported. This value is expected to increase as while both production and consumption of paper have decreased, production has decreased slightly faster than consumption (-1.14% vs -1.05% CAGR 2013-2022), reducing the surplus volume of recovered paper available for export or potentially SAF production. The Food, Green, Wood is set to represent a reasonably rapid build-out of composting facilities. The Plastics scenarios represent a gradual increase in recycling, breaking above the plateau that this category has settled at for the past two decades. Glass and Metals are assumed to remain at the high level already achieved. Others (rubber, leather, others) is a very small category by mass and is forecast to increase very gradually given the difficulty of managing many of the disparate materials this category represents.

The net impact of these scenarios is an increase in recycling rates from 34% (input basis) in 2021 to 36%-42% by 2050. This represents an aggressive deployment of recycling technologies, although the net impact is limited as several categories are already at a high level of recycling. As a result, the increase in recycling rates is overshadowed by the reduction in MSW, decreasing the total volume of MSW recycled. This forecast aligns with historical trends, with the volume of MSW recycled reducing by 12% between 2005 and 2016, despite the recycling rate increasing by +1.3% over the same period[57].

57 https://www.jwnet.or.jp/assets/pdf/en/20190322133536.pdf

The recycling percentage is forecast to gradually increase, although the high rate of MSW reduction results in a net plateau in the mass recycled





Source: ICF Analysis

Aligning with the Japanese waste hierarchy, most of the unrecycled waste is used for thermal recovery or incineration. While the refining of renewable fuels creates a more valuable product, any transition must be managed appropriately. This includes avoiding increasing the cost of the transition by creating excess stranded assets, ensuring incumbent interests are recognised, and deploying technologies at a rate appropriate to their readiness level. Reflecting this, the retirement rate for the Japanese incinerator infrastructure was evaluated, ensuring that the MSW is only considered to be available for SAF production once the existing infrastructure is retired.

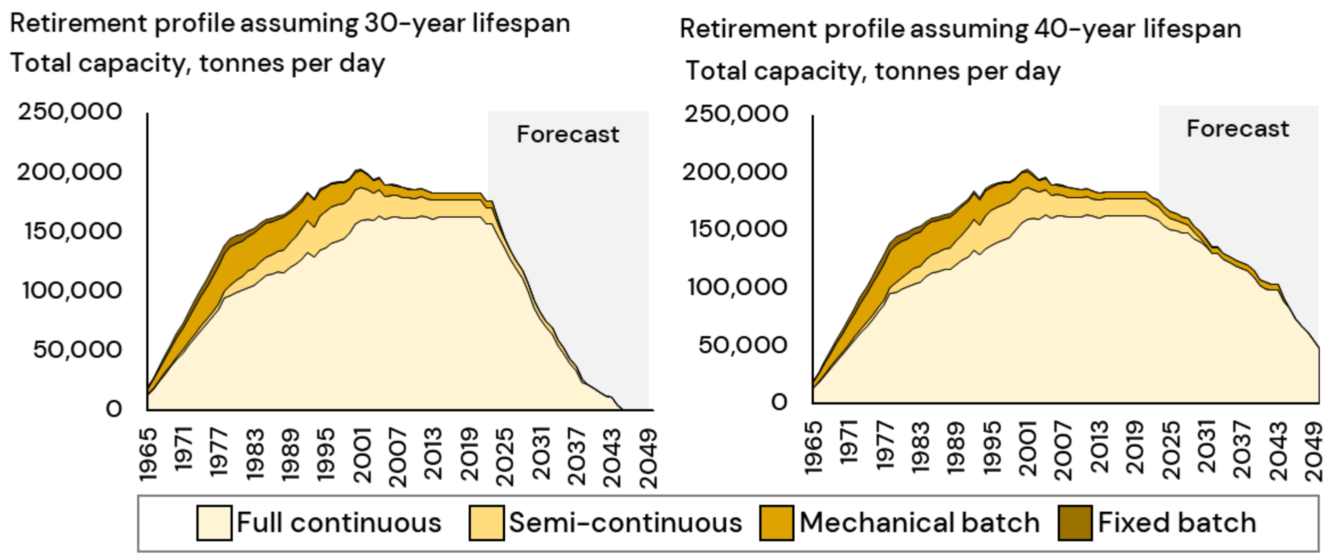
The first waste incinerator was built in Japan in 1924, but the technology was only meaningfully scaled in the 1960s when the national government started providing subsidies[58]. Multiple generations of facilities were built, with improvements to minimize the volume of residual waste, reduce dioxin emissions, and efficiently recover heat and energy[59]. Mirroring the plateau in waste generation at the start of the new millennium, the build-out of new incinerators also plateaued in 2000, followed by a gradual decline as some of the older technologies (batch and non-continuous) and smaller facilities were retired.

To project the retirement trajectory of the facilities, ICF assessed the deployment rate for each technology category. The capacity was assumed to operate for either 30 years (a typical lifetime) or 40 years (a significantly extended lifespan), at which point it was retired. For the historical data[60], retired capacity was assumed to be replaced with new (brown or green field) capacity, which allowed the current age of the incineration fleet to be estimated. The same approach was then used to forecast the decline in capacity as assets reach their end of life, by assuming that each facility operates for the design life and is then shutdown. This trajectory assumes that no additional capacity is built in Japan (although many companies have

58 https://wedocs.unep.org/bitstream/handle/20.500.11822/27294/indExp_Jap.pdf?sequence=1&isAllowed=y
59 https://www.mofa.go.jp/region/latin/fealac/pdfs/4-9_jase.pdf
60 https://www.env.go.jp/en/statistics/contents/2017/E2017_Ch4.pdf

successfully exported the technology to other countries in dire need of better MSW management), and this trajectory therefore represents the rate at which no assets are left stranded during the transition.

The Japanese incinerator fleet was built over the decades following the 1960 and is mid-life, allowing a gradual transition if other technologies are prioritised



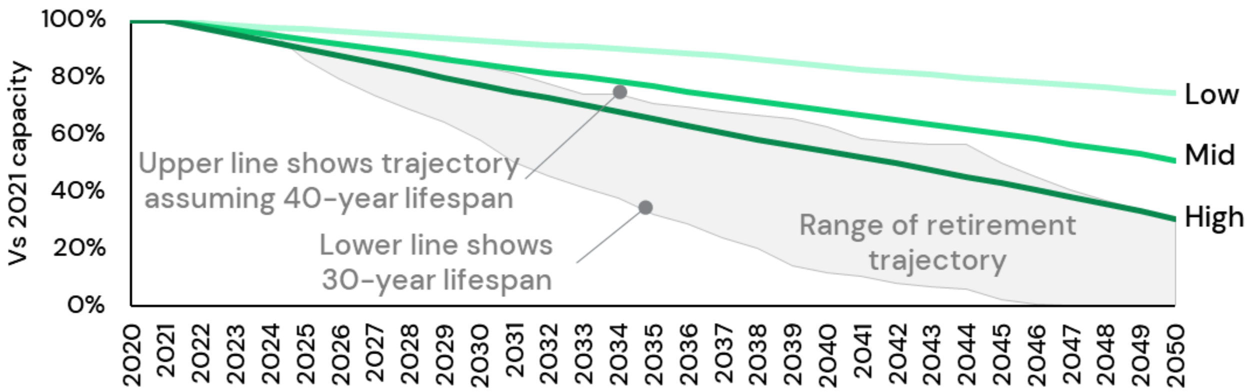
Source: ICF Analysis, https://www.env.go.jp/en/statistics/contents/2017/E2017_Ch4.pdf

The analysis suggests that as capacity plateaued around the year 2000, the fleet reached a steady state, with most assets in their mid-life. This could allow meaningful MSW volumes to be shifted higher in the waste hierarchy, by reducing, reusing, or converting the waste into higher-value products.

These retirement trajectories were used to develop three scenarios for other disposal approaches. It should be recognised that all scenarios assume some level of reduction in incinerator capacity as the volume of MSW produced is reduced and a greater percentage is recycled. These scenarios allow the additional MSW that could be diverted to SAF production to be calculated, with the volume equal to the potentially greater decline in incinerator capacity compared to the decline in non-recyclable waste generation. These three scenarios assume a 25%, 50%, and 70% decline in incinerator capacity (2021 vs 2050). As shown in the following illustration, this decline in incinerator capacity would be slower than if the incinerators were retired at the end of 40-year lifespans, with potential upside if any assets are retired after shorter lifetimes.

The three scenarios to divert MSW to SAF production were developed to ensure no incinerator assets are left stranded

Comparing the MSW transition scenarios to the incinerator asset retirement profile

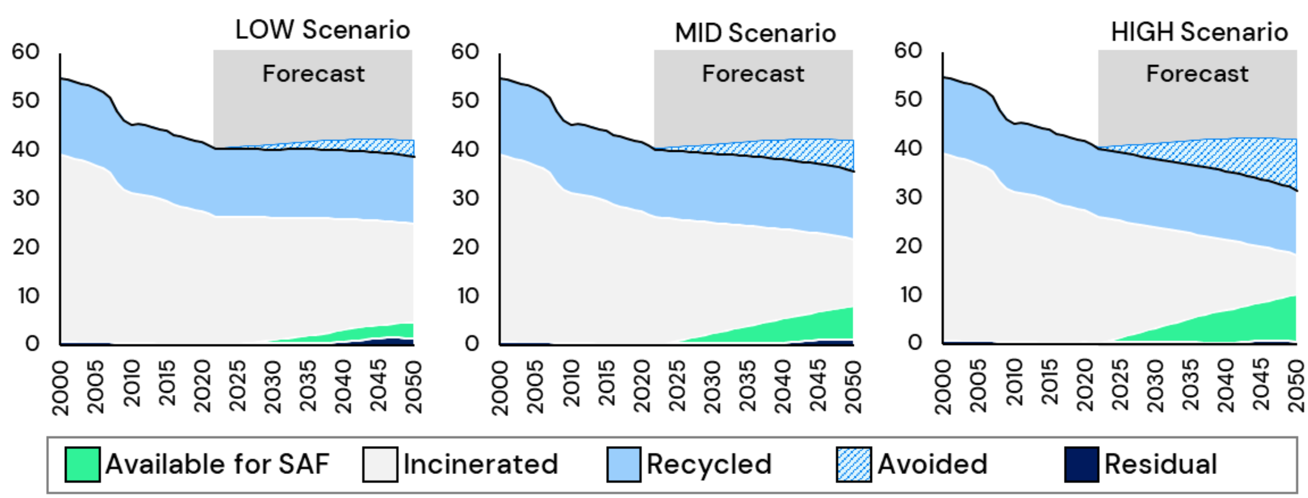


Notes: The transition scenarios as shown in green. The grey area shows the estimates range of retirement trajectories, with the lower line showing the incinerator retirement trajectory assuming a 30-year lifespan, and the upper line a 40-year lifespan.

Combining the estimated MSW baseline production with the reduction in MSW production, increased recycling, and transition from incinerators, allows the volume of MSW potentially available for SAF production to be estimated. These combined scenarios are shown in the following image, with the MSW potentially available for SAF highlighted in green.

The three scenarios project a gradual increase in MSW availability

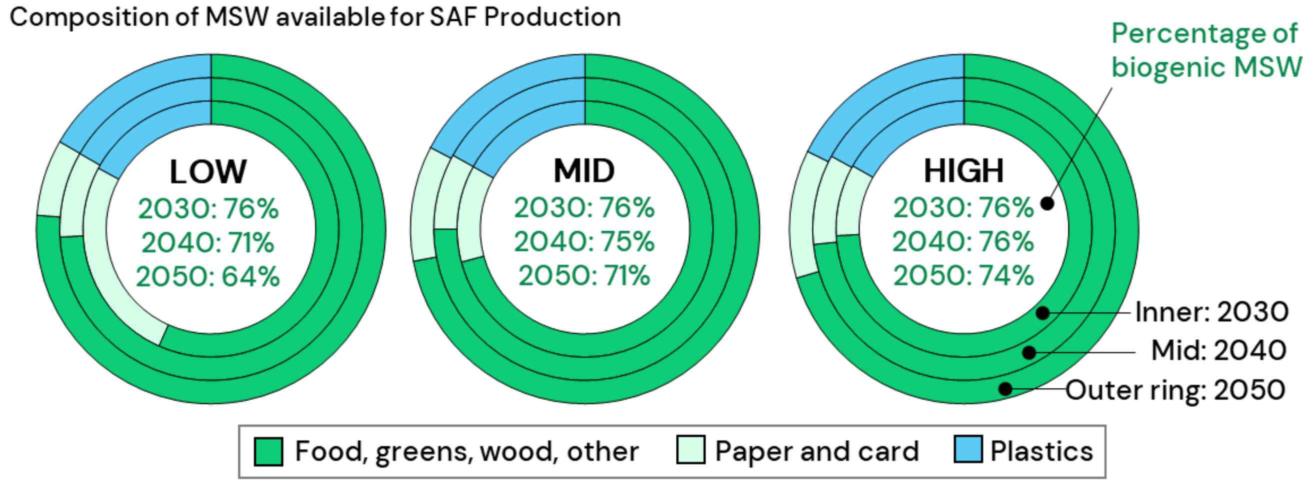
Combined MSW Management scenarios



Source: ICF Analysis

The composition of the waste changes slightly over the analysis period, with the biogenic portion typically reducing very slightly as the availability of plastics and others increases faster than the availability of paper and cards. However, a biogenic portion of 70% plus suggests a reasonable emission reduction, particularly if combined with carbon capture at the facility. The composition for each facility would likely vary with local MSW production and the feedstock contracts.

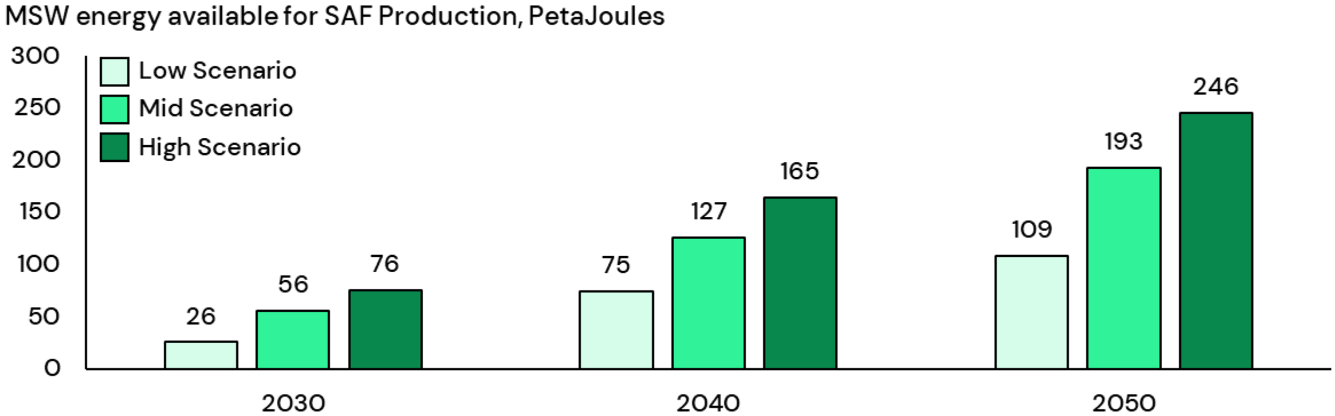
The waste available for SAF production is typically 70%+ biogenic



Source: Combined ICF Analysis. Assuming 'other' wastes are 50% biogenic

Two final adjustments were made to the availability for SAF production, to reflect the immediate availability of waste that is currently exported, and to convert the results into energy to allow comparison with other feedstocks. The two main waste categories exported are post-recycling plastics (which are not separated from the recycled categories shown in the diagram) and recovered paper exports. Approximately 650,000 tonnes of post-recycling plastic is exported, and 1.8 Mt of recovered paper, and while not all of this may be practical or commercially viable, it could provide feedstock to deploy initial facilities. Across the three scenarios, just 20% of each of these exports was assumed available for SAF production, equal to a combined 11.1 PJ. The energy density was assumed as 25 MJ/Kg for food and greens, 19 MJ/Kg, 32.8 MJ/Kg for plastics, 26 MJ/Kg for rubber, leather, and others, and 0 MJ/Kg for Metals and glass.

Forecast of 26-76 PJ of MSW Energy available for SAF in 2030, increasing to 109-246 PJ by 2050



Source: ICF Analysis

4. Discussion

The Japanese waste management infrastructure is highly developed, with all waste collected and managed to maximise the value and avoid residual volumes that must use the scarce remaining landfills. While this means that only small volumes of MSW will be available in the near term, much more significant volumes could become available over the middle and longer term.

However, making these volumes available will require a change from the status quo, driven by a recognition of the position of SAF production in the waste hierarchy and contribution to the indexes established by the Basic Plan for establishing a sound material-cycle society. In particular, SAF production enhances resource productivity and reduces the volume for final disposal. Resource productivity is enhanced due to the significantly higher market value of SAF compared to the heat (729 facilities) and electricity (396 facilities) currently generated. A high-level calculation shows that SAF increases the value per tonne of waste by over 10x compared to electricity generation[61]. SAF production also greatly decreases the volume of residues compared to incineration, supporting the third index set by the regulation.

The most significant change would be to establish SAF production as a higher value than thermal recovery, mirroring similar discussions in other countries. This would prioritize the replacement of the current infrastructure with SAF facilities at the next replacement cycle. Further support could be provided if the Government recognizes the role of SAF production in establishing a sound material-cycle society by awarding grants-in-aid through the existing program. The subsidy rate is usually 1/3 and up to 1/2 for pioneering projects, with between 23,000 and 52,600 million Yen awarded per year (2005-2013) through the program[62].

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61 The Ministry of Environment report that power generation capacity is c. 24 Mt of MSW, which can generate 18,000 GWh per year, which at 10 yen/kWh equals 7,600 Yen/tonne. SAF can produce approximately 75 gallons of fuel per tonne of MSW, and with SAF retailing at c. $8/gal, this is 86,000 Yen/tonne MSW.

62 https://www.env.go.jp/content/900453392.pdf

Agricultural residues

1. Feedstock Description

Agricultural residues are a byproduct from the harvesting and processing of crops and include stalks, husks, straw, cobs, and stems. As their use does not compete with food sources and existing land uses, agricultural residues are an attractive feedstock for the production of cellulosic biofuels, including SAF, that could contribute to meeting the advanced biofuels targets and decarbonisation goals of the transportation sector.

However, the potential large-scale use of crop residues for biofuel production raises concerns about environmental impacts, as crop residues are important in the maintenance and protection of soil quality, including organic matter and nutrients, water and drought resistance, soil temperature and crop yield, as well as soil erosion.

2. Methodology

The volume of agricultural residues available for SAF production is a product of the amount of agricultural activity, the collection rate of the residues, and their use by other industries. These factors were using the following methodology:

1. Assessment of land use and agricultural trends in Japan.
2. Assessment of the regulatory framework guiding the development of the Japanese agricultural industry.
    - Government support policy mechanisms.
    - Agricultural greenhouse gas emissions.
    - Food security mechanisms.
3. Analysis of agricultural residues available by crop.
    - Assessment of the total production of agricultural residues.
    - Analysis of forecast agricultural residue production.
    - Assessment of existing feedstock utilisation.
    - Development of reduction scenarios based on sustainability considerations.
    - Calculating the total volume available for SAF production.

The following sections assess the current and forecast production and then analyse the interaction with other industries. This approach was taken to reflect the different drivers of production, but similar end-use industries.

3. Assessment

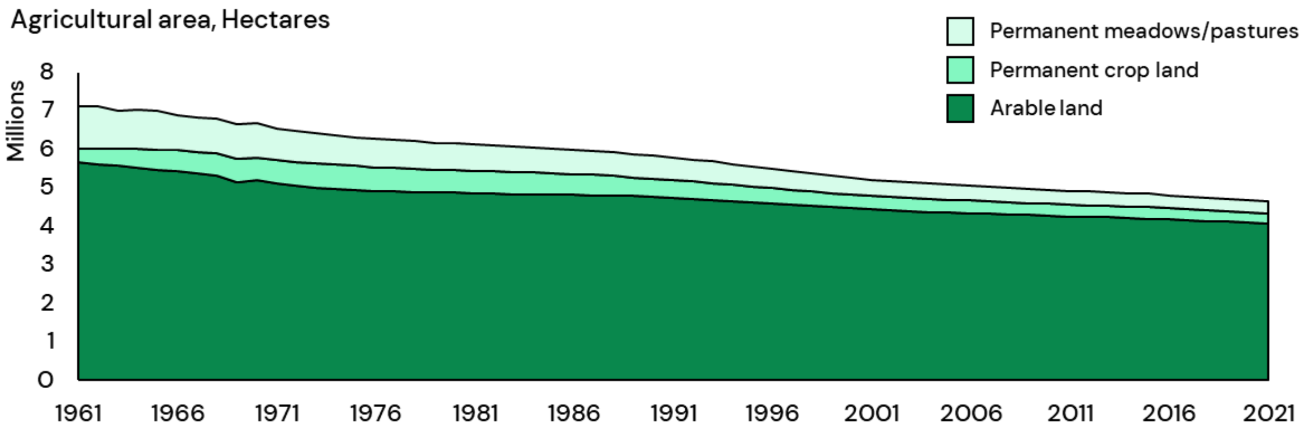
Assessment of land use and agricultural trends in Japan

Japan is an island country, consisting of the main islands of Hokkaido, Honshu, Shikoku, Kyushu and Okinawa, and more than 6,800 smaller islands of various sizes. The combined surface area is close to 38 million hectares. The Japanese landscape is rugged with more than four-fifths (c. 28 million hectares) of the land surface consisting of mountains. Due to Japan's unique location, it is particularly prone to various geological and weather phenomena, including a high number of earthquakes, volcanoes, and typhoon season spells with a total annual precipitation of 1,000 to 2,500 mm per year[63].

In comparison to other countries, Japan stands out with more than two-thirds of their land covered in forests. There are 25.38 million hectares of forest land and fields (c. 67.1%). In contrast, the share of agricultural land is just 11.7% (c. 4 million hectares) and has been declining by almost 0.5% annually. Combined, forests, fields, and farmland cover approximately 80% of the country.

Japan's distinctive climate and geographical characteristics pose a challenge to the agricultural industry. Additionally, the continued decline and ageing population have also led to a shortage of agricultural labour to sustain the workforce, resulting in the abandonment of farmland. As a result, farmland, which excludes unutilised farmland, has declined by 35% since 1961.

Japanese farmland, excluding unutilized farmland, has declined by 35% since 1961



Source: FAOSTAT

The decline in farmland, combined with the shortage of agricultural labour, has boosted imports of many agricultural products. The food self-sufficiency rate in Japan was 37% in 2020 on a calorie basis, the lowest in recorded history, meaning that more than 60% of the Japanese calorie supply depends on imports. The recorded self-sufficiency rate for 2022 was 38%, only 1% higher than the previous year. To counteract the continuous decline in domestic production, the Government of Japan (GOJ) has implemented several policies and regulations to support the agricultural sector, as detailed in the next section.

[63] Climate of Japan — Encyclopedia of Japan (doyouknowjapan.com)

Assessment of mechanisms developed by the regulatory framework guiding the Japanese agricultural industry.

1.1 Government support policy mechanisms

The Ministry of Agriculture, Forestry and Fisheries (MAFF) is the primary ministry responsible for addressing climate change and implementing policies in Japan's agriculture and forestry sectors. In recent years, Japan has utilised the following policy mechanisms to strengthen Japanese agriculture and maximize global reach[64]:

- **Tariffs:** Japan maintains a border protection and domestic price support system for key agricultural products. Japanese tariffs on agricultural products are higher than those on non-agricultural products with average tariffs reaching up to 15.5% in 2019 compared to 2.5% for non-agricultural products[65].

- **Revenue-based payments:** Available to farmers that meet requirements producing rice, wheat, barley, soybean, and other vegetables, if revenues from these crops drop below historic average revenues. Ninety per cent of the difference between current revenue and the past average is compensated by the government and the farmer's reserve fund.

- **Crop diversification payments:** Available to farmers who switch their use of paddy fields from table rice production to other crops, such as wheat and soybeans.

- **Insurance programs:** Available to farmers who experienced yield losses and damage to production facilities from pests and natural disasters.

- **Young and certified farmer programs:** Japan offers three types of support programs to encourage young farmers to enter the agricultural sector. Young farmers can receive an annual grant during their training period, initial operation period, and for additional training. Additionally, farmers can receive certified status for actively engaging in improving farm management. Certified farmers receive benefits such as additional support payments, tax breaks and pension premiums.

- **Direct support payments:** Available for the production of upland crops, such as wheat, barley, soybean, rapeseed, and vegetables. The government provides area payments based on current planting, and output-based payments according to the volume of sales and quality. Additionally, farmers in hilly and mountainous areas can receive direct payments to compensate for the production disadvantage of steep slopes and cultivation plots, to avert the abandonment of agricultural land, and contribute to environmental protection and landscape preservation. Similar payments are awarded to farmers who conduct activities effective in preventing global warming and conserving biodiversity, in conjunction with reducing the use of synthetic fertilizers and pesticides.

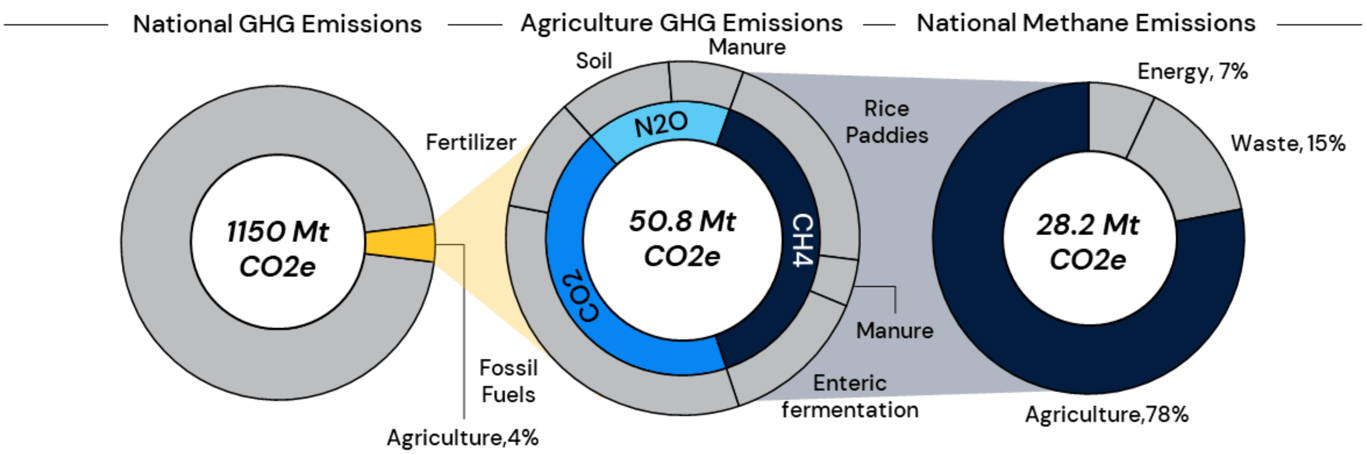
[64] The outlined policy mechanism directly support the annual agricultural output – additional mechanism not mentioned are available by the GOJ

[65] 16. Japan | Agricultural Policy Monitoring and Evaluation 2021 : Addressing the Challenges Facing Food Systems | OECD iLibrary (oecd-ilibrary.org)

1.2 Agricultural greenhouse gas emission mitigation mechanisms

In October 2020, Japan strengthened its GHG reduction target to achieve economy-wide carbon neutrality by 2050. In support of their target, Japan published the Green Growth Strategy[66], which includes agriculture as one of the fourteen priority sectors. MAFF has since published guidelines which outline the reduction of GHG emissions from the agricultural sector to be achieved in the following ways: reducing fuel consumption, disseminating water management methods for paddy fields to lower methane emissions, and improving fertilizer use efficiency to reduce nitrogen. For reference, in 2020, agriculture accounted for about 4% of the national total greenhouse gas (GHG) emissions. Methane production, from rice cultivation and livestock production, accounted for most emissions by GHG type, totalling 80%.

Agriculture accounts for about 4% of national GHG emissions and about 80% of methane emissions



Source: ICF Analysis, MAFF, Japan Ministry of Environment, 2020 data

In alignment with the Green Growth Strategy, the energy sector passed the Act for Partial Amendment of the Electricity Business Act for the Establishment of a Resilient and Sustainable Electricity Supply System. This act took measures to build a disaster-resilient power distribution system and revised the already existing Feed-In Tariff (FIT), in addition to launching a new system, the Feed-In Premium (FIP). Both the FIT and FIP systems facilitate the development of renewable power projects, including the use of biomass fuels. In early 2023, METI added agricultural residues, such as corn straw pellets, as eligible under the schemes. METI is still examining whether to add straw, rice straw, and rice husk to the schemes as they are currently used in other industries[67].

[66] https://www.meti.go.jp/english/policy/energy_environment/global_warming/ggs2050/index.html
[67] Japan adds new biomass fuels, certificates to FiP, FiT | Argus Media

1.3 Food security mechanisms

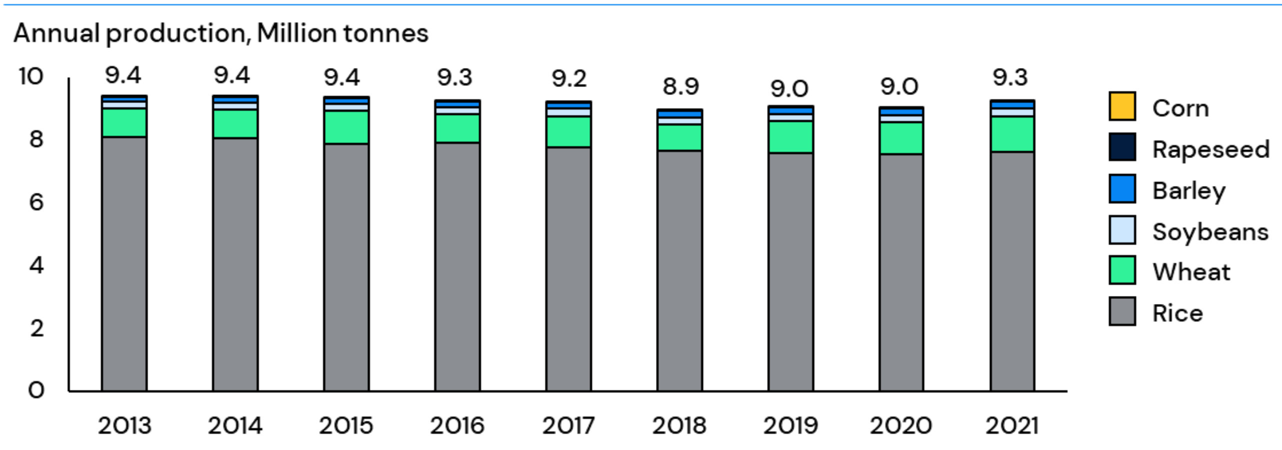
The Basic Plan for Food, Agriculture and Rural Areas, which establishes Japan's overall agricultural policy for the next decade, was revised in 2020[68]. The plan focuses on the sustainability of agriculture, rural communities, and succession planning, and calls for the public to support agriculture. It also sets targets to increase domestic production of all products except for rice. Productions with expected consumption declines and increased production targets, such as wheat, barley, and soybeans, are expected to replace imports in the domestic market or be exported. The sustainable development of the agriculture portion of the plan is to reinforce production and streamline supply chains through the application of smart agriculture and digital technologies to meet changes in demand structure and to strengthen measures for climate change.

Analysis of agricultural residues available by crop

1.1 Assessment of total production of agricultural residues

Since agricultural residues are a byproduct of primary crops, the volume of residues available is directly related to the annual agricultural output. In Japan, the rice crop dominates in terms of average land use and production value with an average agricultural output of 75%. Additional crops produced in Japan include corn, wheat, barley, rapeseed, soybean, fruits, and vegetables. Fruit and vegetable production was not considered for this analysis, as the production values were considered negligible compared to other crops. Japan's overall demand and production of grain and feed have remained static over the past decade.

Annual agricultural production has stayed static the past decade, with rice production accounting for 75% of agricultural output



Source: USDA Foreign Agricultural Service, MAFF

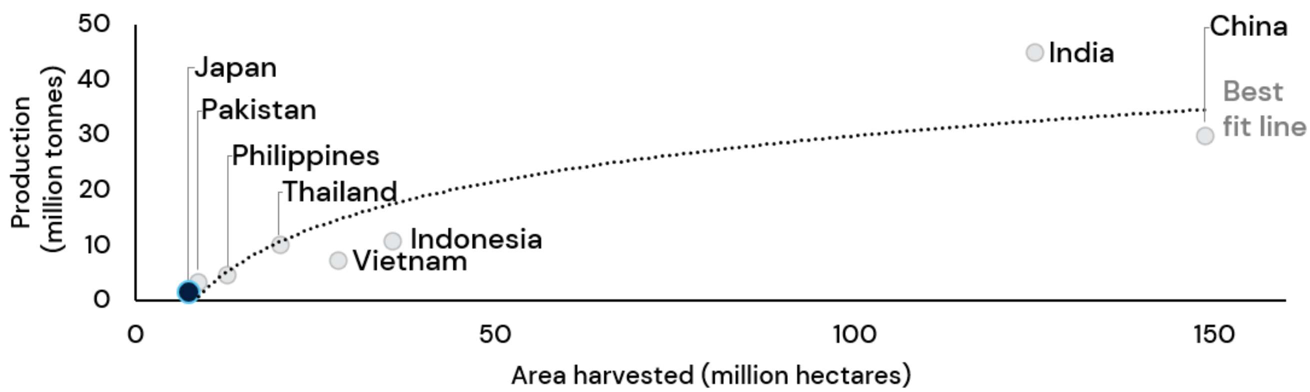
According to the Asian Biomass Handbook, an estimated 3 billion tonnes of agricultural residues are produced globally, with rice accounting for the largest production of 836 million tonnes[69]. Rice is a widely recognized

[68] https://www.maff.go.jp/e/policies/law_plan/attach/pdf/index-13.pdf
[69] https://www.build-a-biogas-plant.com/PDF/AsianBiomassHandbook2008.pdf

staple food crop, particularly prevalent in Asia, Sub-Saharan Africa, and South America. With 756 million tonnes produced globally in 2019[70], rice is the third-most produced agricultural crop in the world. The majority of today's rice production comes from China (ca. 148 million tonnes in 2019[71]) and India (c. 125 million tonnes in 2021[72]). Japan is ranked the ninth-largest producer, producing 7.5 million tonnes in 2021[73].

Japan is one of the top nine rice producers globally, producing 7.5 million tonnes in 2021

Annual production vs. Area harvested, 2021



Source: OECD Agriculture Outlook, 2021-2030
https://stats.oecd.org/Index.aspx?DataSetCode=HIGH_AGLINK_2021

Produced agricultural residues include field residues and process residues. Field residues are residues that are present in the field after the process of crop harvesting. These include stalks, stems, and straw. Process residues are residues produced after the crop is processed into an alternative valuable source. These include husks, cobs, roots, and bagasse.

The total amount of agricultural residues available was calculated utilising the crop yield and the residue-production-ratio RPR, also defined as the above-ground harvestable biomass residue to the primary crop yield. Several studies reviewed outline that the RPR is better represented as a function of a primary crop yield than as a fixed value, therefore an exponential function representative of each crop was utilised[74]. This is to best encompass factors such as soil type, weather conditions, harvesting practices, and primary crop yield. Utilising this methodology, the total amount of agricultural residues produced in 2021 is estimated to be 12.7 million tonnes.

[70] https://www.weforum.org/agenda/2022/03/visualizing-the-world-s-biggest-rice-producers/
[71] https://stats.oecd.org/Index.aspx?DataSetCode=HIGH_AGLINK_2021
[72] https://stats.oecd.org/Index.aspx?DataSetCode=HIGH_AGLINK_2021
[73] https://stats.oecd.org/Index.aspx?DataSetCode=HIGH_AGLINK_2021
[74] Study referenced for equations: crop-residues-are-a-key-feedstock-to-bioeconomy-but-available-methods-for-their-estimation-are-highly-uncertain.pdf

1.2 Analysis of Forecast Agricultural Residue Production

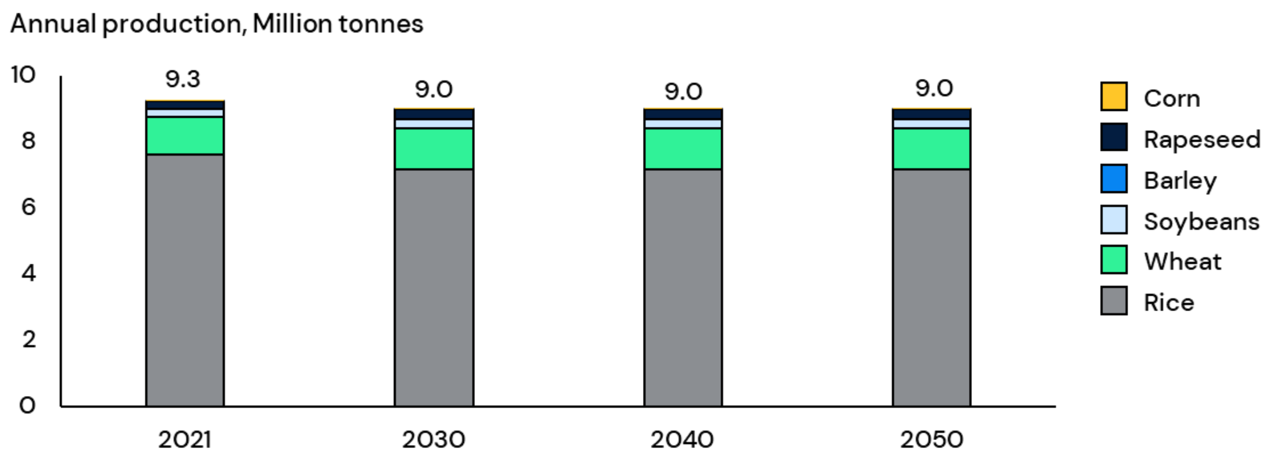
Forecasted agricultural production was determined utilising the 2020 Basic Plan for Food Agriculture and Rural Areas, as well as the Food Security Reinforcement Policy Framework. The 2030 Japanese Fiscal Year (JFY) production targets are higher than current levels for all commodities, except for rice, as outlined in the table below.

Table 1: 2030 production targets from the 2020 baseline

Commodity	+/-	Percentage
Rice	-	6%
Corn	+	32%
Wheat	+	9%
Barley	+	32%
Rapeseed	+	25%
Soybean	+	16%

Due to rice production making up 75% of the total agricultural output in Japan, the total production in 2030 is expected to decrease by an estimated 3%, between 2021 and 2030. Additionally, production targets for 2040 and 2050 were assumed to remain static from 2030, due to the assumption of government support driving increased production, countered by a decrease in agricultural product consumption related to population decline.

Annual agricultural production is expected to decrease by 3% between 2021 and 2030 and remain static until 2050



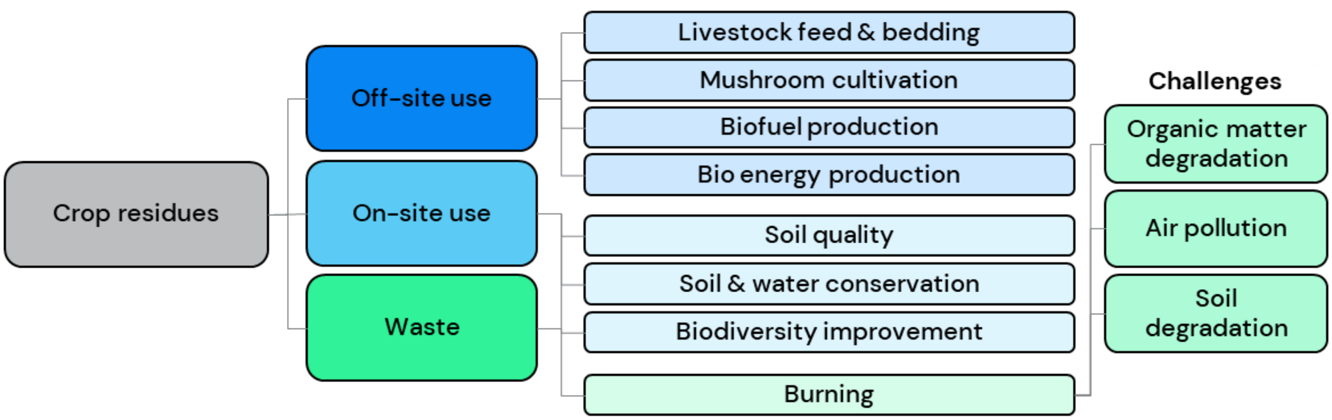
Source: ICF Analysis, USDA Foreign Agricultural Service, MAFF

1.3 Assessment of existing feedstock utilisation

Agricultural-based industries produce a significant volume of residues each year. If these residues are released into the environment without proper management procedures, they can lead to environmental pollution and cause harmful effects on human and animal health. Such challenges include increased methane production from the degradation of rice residue in rice paddy fields, air pollution from unnecessary burning of agricultural residues, and soil degradation. Crop residue management should be done to benefit the grower without negatively impacting the health and productivity of the soil, as well as the environment.

Management procedures can be split into three different categories: (1) off-site, (2) on-site, and (3) waste. On-site use can improve soil productivity and crop production by providing nutrients, improving water availability, and protecting from erosion. Off-site use can provide valuable resources of significant economic value, such as animal bedding and supplemental feed for livestock, renewable energy production through the conversion into biofuels (i.e. bioethanol), cultivation of edible fungi or mushrooms, and others. When residues are neither used off-site nor on-site, they are often disposed of as waste by burning, a practice used by farmers as the most convenient, cheap about time, labour and finance, and beneficial for control of the feed. Such traditional agricultural management procedures, however, do not provide any economic returns to the farmer and result in poor soil health conservation and maintenance.

Agricultural residue management is split into three categories: off-site use, on-site use, and waste



Source: ICF analysis

According to Japan's Third Basic Plan for Promoting Biomass Utilisation[75], the amount of sustainably collected agricultural residues is currently being used by other industries for feed, fertilizer, bedding, and biofuel production. Agricultural management procedures emphasize profitability, sustainability, technical feasibility, and adoption potential. Additionally, it can be assumed that additional agricultural residues will be added as eligible under the FIT and FIP schemes in the upcoming years, to support the production of renewable energy from biofuels.

[75] https://www.maff.go.jp/e/policies/env/attach/pdf/biomass-2.pdf

1.4 Development of reduction scenarios based on sustainability considerations

According to Japan's Third Basic Plan for Promoting Biomass Utilisation, 31% of agricultural wastes are collected today, with a further 61% ploughed back into the land to maintain soil health. The remaining 8% of residues are not used. The plan outlines an aim to increase the amount of energy used for fuel production and to achieve a sustainable collection rate of 45% by 2030 while monitoring the progress of technologies for energy use and material use. With the promotion of smart agriculture technologies and sustainable production systems, as outlined in MAFF's Summary of the Annual Report on Food Agriculture and Rural Areas in Japan, it is expected that fewer agricultural residues will be required to produce a higher crop yield. Therefore, the forecast sustainable collection rate is to increase to 50% by 2050.

Agricultural residues are primarily being used by other industries for feed, bedding, fertilizer, and biofuel production. Japan's Third Basic Plan for Promoting Biomass Utilisation outlines a goal of utilising up to 10% of biomass (including agricultural residues) for SAF production. Although agricultural residues will be re-allocated from other industries to meet this goal, it can be assumed that with an increase in agricultural production and collection, as well as the production of by-products such as naphtha and renewable diesel from SAF production, these products will be used across the different industries.

Utilising these variables, three scenarios were developed, (1) low-scenario representing the current amount collected (2) mid-scenario representing the amount collected with government support to the agricultural industry and increase in energy production from biomass (3) high-scenario representing a continued increase in government support and energy production with advancements in farming technologies. These assumptions were utilised to build the following scenarios estimating the potential percentage of agricultural residues that can be sustainably collected and reallocated from different industries.

Table 2: Scenarios estimating the potential percentage of Agricultural Residues that can be sustainably collected and allocated to SAF production

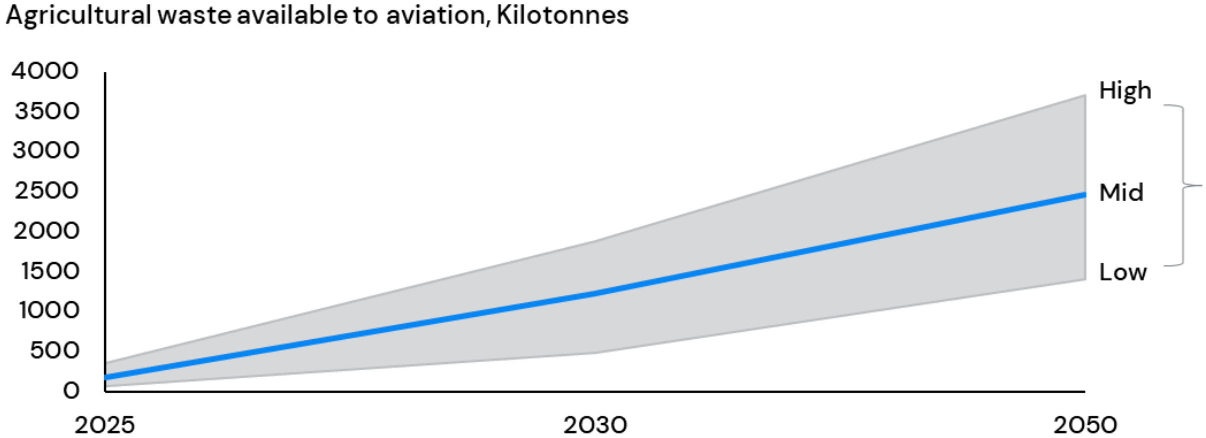
	Description	Scenario	2025	2030	2040	2050
[1]	Baseline – Allowed removal to remain soil health boundaries	Low	60%	60%	60%	60%
		Medium	60%	60%	60%	60%
		High	60%	60%	60%	60%
[2]	Baseline – Sustainable collection rate	Low	31%	40%	45%	50%
		Medium	31%	45%	50%	55%
		High	31%	45%	55%	58%
	Increased collection - % growth	Low	0%	9%	14%	19%
		Medium	0%	14%	19%	24%
		High	0%	14%	24%	27%
	Increased collection - % of existing	Low	31%	31%	31%	31%
		Medium	31%	31%	31%	31%
		High	31%	31%	31%	31%
	Available to aviation - % growth	Low	25%	25%	25%	25%
		Medium	35%	35%	35%	35%
		High	50%	50%	50%	50%
	Available to aviation - % of existing	Low	2%	5%	10%	20%
		Medium	5%	15%	25%	35%
		High	10%	25%	35%	50%
[3]	Resulting %	Low	0%	2%	4%	5%
		Medium	0%	5%	7%	8%
		High	0%	7%	12%	14%
[3]	% of existing	Low	1%	2%	3%	6%
		Medium	2%	5%	8%	11%
		High	3%	8%	11%	16%
	Total per cent allocation	Low	1%	4%	7%	11%
		Medium	2%	10%	14%	19%
		High	3%	15%	23%	29%

[1] – Sustainable crop removal pertains to a certain amount of crop residue being left on the ground to ensure soil health – this depends on the type of crop and yield, topography, climate, management, and tillage practices. An average percentage was applied encompassing all factors.
[2] – Sustainable collection rate pertains to the amount of residues that can be collected without affecting the soil health. The values must remain below the allowed crop removal rate.
[3] – Values are the combined percentage of increased collection and availability to aviation.

1.5 Calculating the total volume for SAF production

Based on the three development scenarios, low, medium, and high, the total amount of agricultural residues available to the aviation industry was determined to be an estimated 70-354 kilotonnes in 2025, increasing to 1399-3707 kilotonnes in 2050.

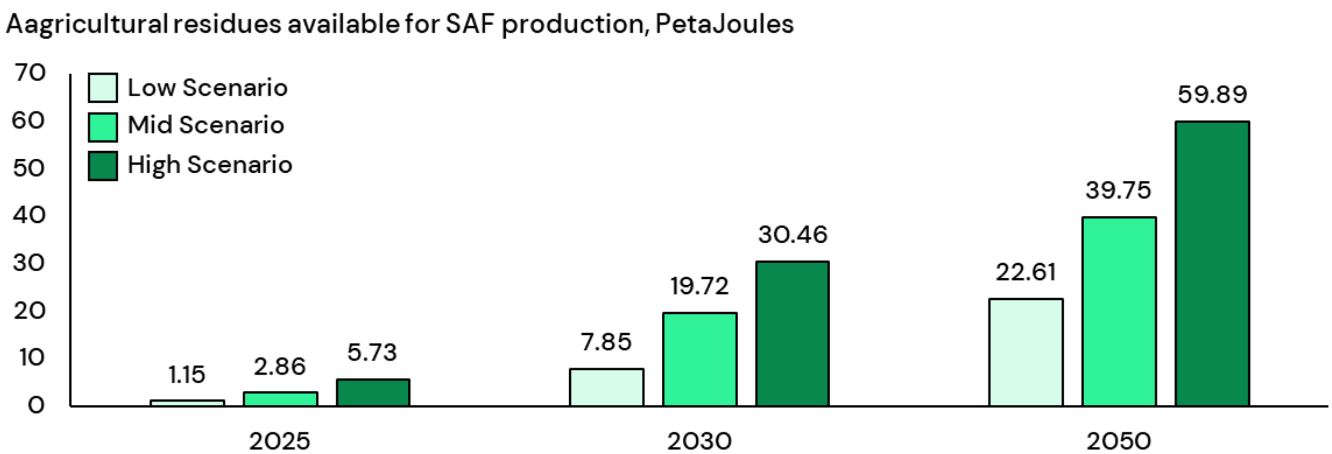
The volume of agricultural residues available to aviation ranges from c. 70-354 KT in 2025 to 1399-3707 KT in 2050



Source: ICF analysis

The total amount of agricultural residues available for SAF production in petajoules was calculated utilising the volume of agricultural residues available per crop, multiplied by the respective moisture content to determine the total amount of dry residue. The values were then converted to energy utilising their respective lower heating value (LHV) in exajoules per million tonnes. Exajoules were then converted into petajoules utilising a conversion ratio. Overall, the total amount of energy available for SAF production is expected to increase from 5.7 PJ by 2025 to 59.9 PJ by 2050, assuming an increase in government support for the agricultural industry, the use of agricultural biomass for energy production, and advancements in farming technologies.

Forecast of 1.2-5.7 PJ of agricultural residues in 2025 increasing to 22.6-59.9 PJ in 2050



Source: ICF Analysis

Woody biomass

1. Feedstock Description

Woody biomass refers to organic materials derived from trees and woody plants, primarily composed of lignocellulosic matter such as cellulose, hemicellulose, and lignin. These materials encompass various forms, including tree trunks, branches, bark, and wood chips, and are utilised as feedstock for biofuel production processes. Woody biomass is a valuable and renewable resource, offering a sustainable alternative to fossil fuels, and can be converted into biofuels like wood pellets, and biochar, or through thermochemical processes such as pyrolysis and gasification to produce bioenergy in the form of heat, electricity, or liquid biofuels like bioethanol and bio-oil.

2. Methodology

Japan has developed a comprehensive system to use domestic and imported woody biomass for energy. This developed supply chain offers some opportunity to use woody biomass for SAF production, however, significant biomass generation capacity is under construction in Japan which may consume the significant majority of available woody biomass. Increasing deployment of renewables, batteries, and the resurgence of nuclear generation may gradually soften demand, and increased domestic availability may be possible. This opportunity was estimated through the following analyses:

1. Overview of woody biomass in Japan
2. Analysis of current sourcing and use of woody biomass for energy
    a. Assessment of the current domestic supply and imports
3. Analysis of the outlook and potential for SAF production

3. Assessment

Overview of woody biomass in Japan

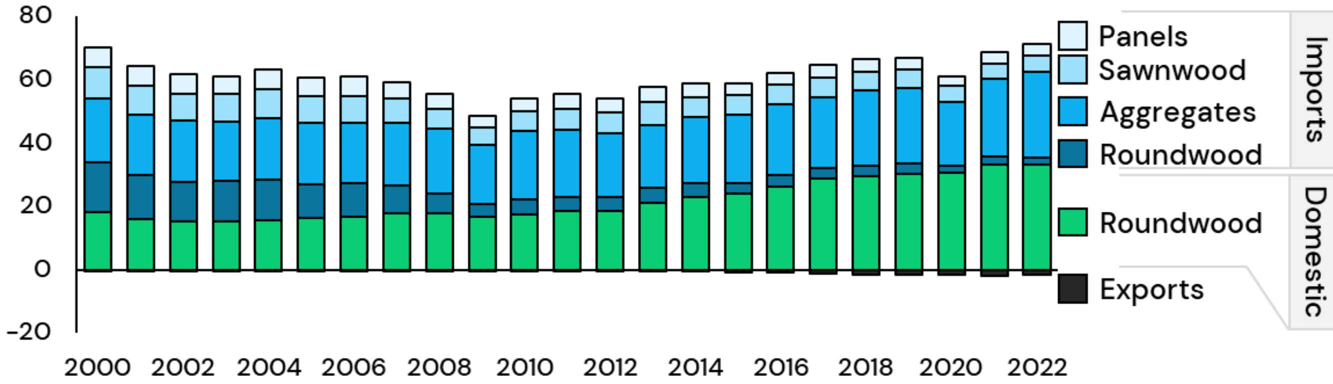
Japan has over 25 million hectares of forest and is also paradoxically one of the top importers of wood and related products. In the 1950s, almost all wood was supplied domestically, but as trade was liberalized and demand strongly grew in line with the wider economy, the volume of imports rapidly increased. The decades through the 1970s saw strong growth in imported logs, which was gradually substituted with imports of products as the exporting countries moved up the value chain. In 2002, the wood self-sufficiency rate reached a nadir of 18.8%[76].

Several factors have driven a gradual resurgence in domestic production. The Kyoto Protocol was adopted in 1997, which drove increased awareness of the role of biomass and was followed by the Japanese government implementing the *Law Concerning Special Measures for Promotion of the Use of New Energy* in 2001, and the *Biomass Nippon Strategy* in 2002. The Feed-in tariff (FIT) was implemented in 2012, which further stimulated the use of woody biomass (particularly wastes and residues) for electricity production. Areas of planted forest have matured, allowing domestic production to increase with demand, although the self-sufficiency rate has remained low at c. 36%.

[76] https://www.intechopen.com/chapters/72955

Domestic production has increased, but nearly two-thirds of wood is still imported

Japan wood production, import, and export, Selected categories, Million cubic meters



Source: https://www.fao.org/faostat/en/#data/FO

Wood use in Japan is dominated by construction, paper, and energy. Half of all dwellings in Japan are detached houses (53.6%), of which almost all (92.6%) are wood-framed. The other half are apartments, which are mostly (72.3%) steel-framed concrete structures[77]. Building wood-frame dwellings is a key source of demand, and significant waste wood is generated during their construction and end-of-life demolishment.

The paper industry requires fresh wood fibres, which are then combined with recycled paper. Some of this waste could be used for energy and is discussed in the section on Municipal Solid Waste. Some black liquor is created during the production process, much of which is used for energy generation. Woody biomass use for energy has rapidly increased with the introduction of the FIT scheme, fueled by both increasing domestic supply and imports.

Analysis of current sourcing and use of woody biomass for energy

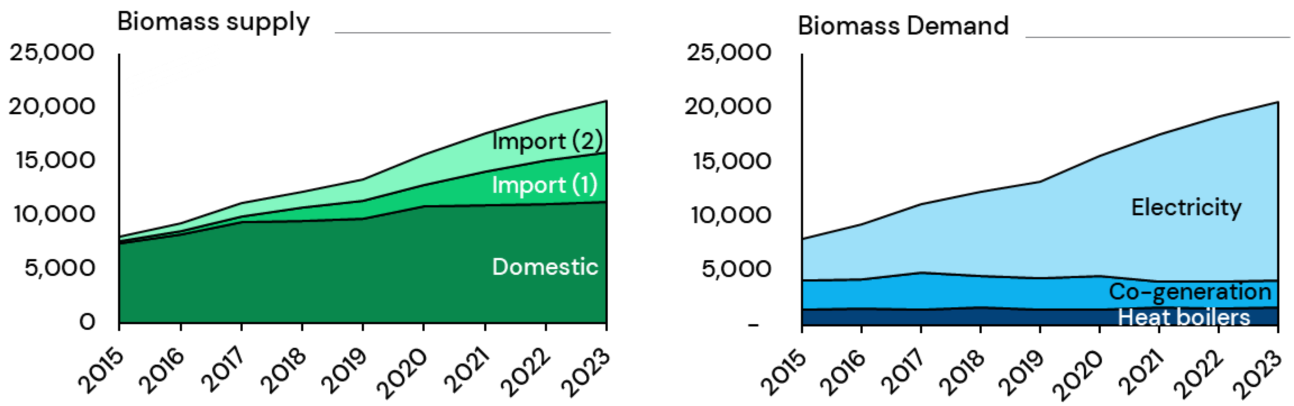
The Feed-In tariff has been crucial to drive the use of biomass for energy. While it originally focused on solar, the expansion of the FIT in 2012 opened the scheme to include biomass, wind, geothermal and small-scale hydro. Biomass is eligible for electricity production in stand-alone plants, or co-firing alongside fossil fuels (e.g. in coal power stations), and almost all demand growth has originated from stand-alone generators. Between 2015 and 2023, demand increased by 20.2% CAGR, equivalent to growth of approximately 1.58 million tonnes of biomass every year. Heat generation is not covered by the FIT, so this has remained at relatively low levels[78].
This demand has been met through an expansion of domestic supply, and growth in imported chips and pellets (1) and imported palm kernel shells (2).

[77] https://www.stat.go.jp/english/data/handbook/c0117.htm

[78] https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Japan%20Biomass%20Annual%202023_Tokyo_Japan_JA2023-0071

Electricity demand has driven increased (imported and domestic) biomass use

Annual biomass consumption, Bone-dry '000 tonnes

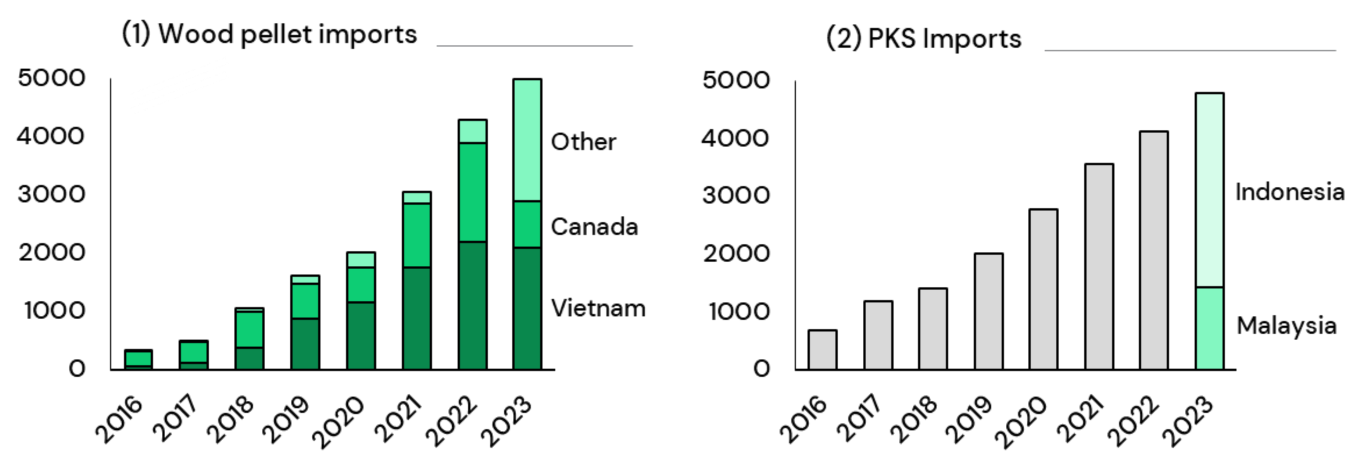


Notes: Import 1 = Imported chips and pellets. Import 2 = Imported Palm Kernal Shells (PKS).
Source: Forest Agency, ANRE, Japan Customs, analysed by the USDA

These imports have come from a diverse selection of countries. Much of the wood pellet imports are from Vietnam (particularly the fast-growing acacia wood), followed by Canada. The Palm Kernel Shells (PKS) are exported by Indonesia (70%) and Malaysia (30%).

Wood pellet and PKS imports for electricity generation have dramatically increased

Wood and Palm kernel Shell Imports, Bone-dry '000 tonnes

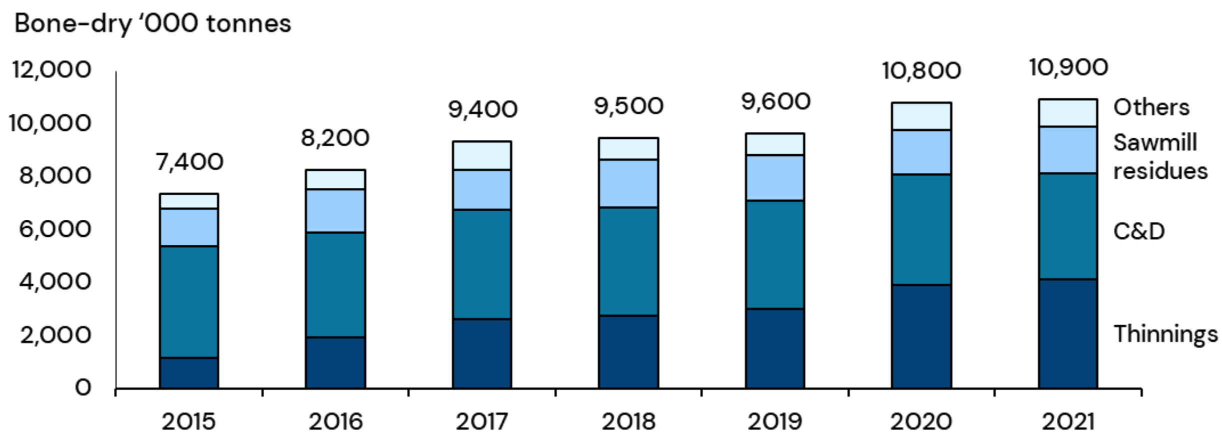


Source: Wood Pellets: https://www.maff.go.jp/e/policies/forestry/attach/pdf/index-14.pdf, PKS: https://www.fas.usda.gov/data/japan-clarifying-japanese-imports-palm-kernel-residues

While these imports do not contribute to reducing energy dependence, they do diversify supply, as none of these key importers are in the top 10 importers of fossil fuels to Japan[79]. They also contribute to emissions reduction, particularly with increasing emission reduction requirements implemented by METI.

Domestic supply has grown at a slower but consistent rate. The availability of construction and demolition (C&D) biomass and sawmill residues has remained flat, with the growth driven by an increase in the thinnings from 1.1 Mt/yr in 2015 to 4.1 my/yr in 2021. This represents an important maturation of the domestic supply chain, with consistent increases of c. 0.5 Mt/yr.

Domestic wood chip has gradually increased, driven by thinnings



Source: Forest Agency, ANRE, Japan Customs, analysed by the USDA

Analysis of the outlook and potential for SAF production

The availability for SAF production is a result of the potential supply of woody biomass, and any surplus (created by regulation or market forces) compared to the demand from other sectors. This analysis investigated three factors expected to impact supply and demand: (1) increasing sustainability requirements, (2) growing electrical generation, and (3) growth in domestic supply.

1.1 Increasing sustainability requirements may constrain supply

The sustainability requirement for biomass eligible for the FIT program has been incrementally developed to ensure the contribution to decarbonisation, sustainability, and energy security. Since 2012, the Ministry of Agriculture, Forestry, and Fisheries (MAFF) has imposed requirements for wood pellets (JA2019-0124), including chain of custody certification. This was strengthened in April 2023 with a requirement that biomass power generators calculate lifecycle GHG emissions, supported by default values published in JA2023-0007[80]. New

79 https://app.archieinitiative.org/
80 https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Japan%20Biomass%20Annual%202023_Tokyo_Japan_JA2023-0071

projects are required to demonstrate a 50% GHG emission reduction and a 70% reduction from 2030[81]. Additional requirements will be imposed for PKS used under the FIT program from April 2024.

These criteria are expected to gradually constrain supply, although as the emission threshold only applies to new generation the impact will be limited, with perhaps the greatest impact on low-density feedstocks shipped long distances, such as the biomass shipped across the Pacific from Canada. Some feedstocks have already been excluded for failing other criteria, including all Russian wood pellets/chips following their designation of conflict wood due to the invasion of Ukraine. The Vietnam supplier An Viet Phat (AVP) has also been impacted due to allegations that the company sold wood pellets with false certificates, removing a source of c. 0.5 t/yr from Japanese imports. This increasing regulation is necessary to ensure the environmental benefit but may constrain the available biomass for power generation and potential future SAF production.

1.2 Growing power generation will increase demand

Considerable additional biomass electrical generation capacity is approved under the FIT scheme, which will considerably increase demand. In December 2022 ANRE[82] suggested that 586 plants were operational, with an installed capacity of 4.1 GW, and a total of 900 biomass power plants were approved, with a total capacity of 8.3 GW.

Several major plants are expected to come online in 2023, including Kansai Electric's 200MW Aioi Power Station Unit 2 (wood pellets), and Renova's four new 75MW biomass plants in Sendai, Tokushima, Ishinomaki, and Omaezaki, which will use wood pellets and PKS. This additional capacity will meaningfully increase demand for woody biomass and PKS in Japan over the short term.

Demand over the mid and long term is less certain. While decarbonisation targets support the use of biomass, its use for electrical generation may become increasingly uncompetitive compared to other forms of renewable energy generation. The IEA suggest that the levelized cost of electricity (LCOE) is a median of 118 USD/MWh for biomass in 2020, compared to 56 USD/MWh for utility-scale solar PV and 88 USD/MWh for offshore wind. The business case in Japan will vary with land costs and availability, the need for stable supply, and feedstock prices, but strong growth in renewables (in Japan and worldwide) may support a peak and gradual phase-down of biomass use for electrical generation over the next three decades[83].

1.3 Increased domestic supply of woody biomass

The potential supply of energy from woody biomass is estimated at 630 PJ/yr, which is significantly greater than the use of c. 250 PJ/yr in 2005[84]. While the use has gradually increased over the last decade, this indicates that the sustainable potential could be almost double the current use.

Several factors have held back the industry. The mountainous terrain provides an immediate challenge, and a low-density forest road network (19.7 m/ha, e.g. 89 m/ha in Austria) hinders logistics. Relatively low levels of

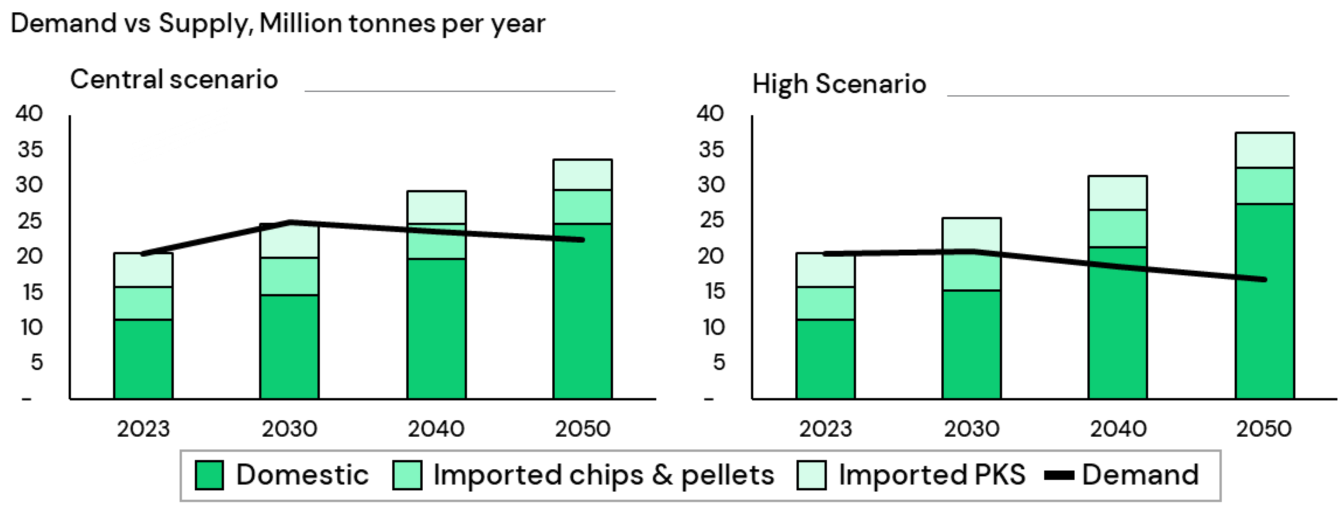
[81] https://news.mongabay.com/2022/05/as-biomass-burning-surges-in-japan-and-south-korea-where-will-asia-get-its-wood/
[82] https://www.fit-portal.go.jp/PublicInfoSummary
[83] https://www.iea.org/reports/projected-costs-of-generating-electricity-2020
[84] https://www.intechopen.com/chapters/72955

automation and comparatively high wages increase the cost, with an estimated logging cost of 58-85 USD/m^3 in Japan, compared to 12-22 USD USD/m^3 in Sweden and 29-50 USD/m^3 in Austria. The drive for sustainability and domestic energy supply may lead to investment and development of the supply chain, opening up greater domestic supply to replace fossil fuels.

4. Discussion

Increasing demand for biomass power generation is expected to drive demand for domestic supply and imports. In the low scenario, this is expected to exclude the use of woody biomass for SAF production, with all supply consumed by electrical generation.

Increasing domestic supply and tapering power demand may allow use for SAF



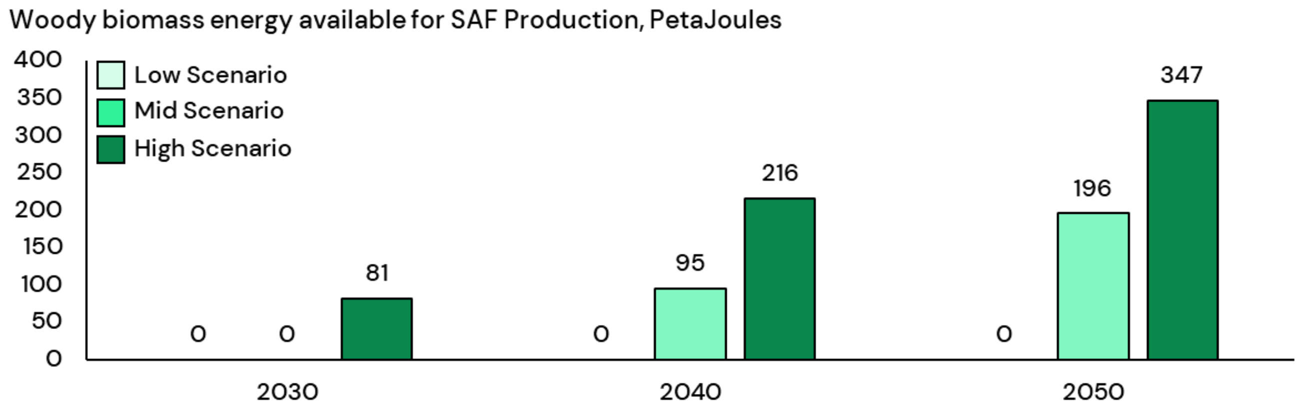
Source: ICF Analysis

In the central scenario, domestic supply is expected to increase by c. 0.5 Mt/yr, which is in line with the average historical increase in domestic thinnings between 2015 and 2021 (0.49 Mt/yr, low of 0.1 Mt/yr and high of 0.88 Mt/yr). Imported pellets and chips are forecast to increase to meet demand in 2030, before declining by 1% per year as sustainability criteria become more constraining and domestic supply is prioritized. The central demand scenario forecasts an increase of 20% by 2030 as additional facilities come online, followed by a gradual decline of 0.5% per year as other forms of renewable energy become more competitive.

The high scenario forecasts a slight increase in domestic supply, with 0.55 Mt/yr added (a 10% increase over the historical rate of growth), with PKS and pellet imports decreasing by 0.5%/yr over the next decades. Demand plateaus out to 2030, before declining by 1% per year over the following two decades.

These scenarios combine to suggest a significant opportunity for woody biomass, but a wide range driven by the demand from power generation and the development of a domestic supply chain.

Significant woody biomass may be available if SAF production is supported



Source: ICF Analysis

Novel feedstocks (i.e. Algae)

1. Feedstock Description

Algae for biofuel production refers to certain types of microorganisms, primarily photosynthetic microalgae and cyanobacteria, that are cultivated and harvested to extract lipids or carbohydrates, which can be converted into renewable biofuels. Algae are a promising feedstock for biofuel production due to their rapid growth rates and high oil or carbohydrate content, making them a sustainable and environmentally friendly alternative to fossil fuels. The conversion processes may include the transesterification of lipids into biodiesel or the fermentation of carbohydrates into bioethanol or other advanced biofuels.

Despite significant progress over the past decade, algae researchers estimate that the breakthroughs required to affordably produce algae biofuels at scale are 1-2 decades away, with billions required to bring the technology to maturity. While this limits the near-term opportunity for Japan, this analysis was conducted to assess the longer-term opportunity to use SAF from algae to domestically produce SAF.

2. Methodology

The total volume of algae available for SAF production in Japan was determined using the following factors and methodology:

4. Assessment of SAF production from algae
5. Analysis of the outlook of SAF production from algae in Japan

The following sections provide a detailed overview of algae production as well as a potential outlook for the utilisation of algae for SAF production in Japan.

3. Assessment

Assessment of SAF production from algae

1.3 Different algae strains

Researchers are working to identify promising strains with the properties necessary for deployment, including temperature optimum for Summer and Winter crops, growth in either salt water or fresh water, and genetic tractability. Research for the mass production of algae oil mainly focuses on microalgae (organisms capable of photosynthesis that are less than 0.4 mm in diameter), as opposed to macroalgae, such as seaweed. The preference for microalgae is largely due to faster growth rates, and a higher oil content per strain, although the amount of oil in each strain varies significantly.

The different algae strains viable for SAF production include the following:

- **Botryococcus braunii:** This strain can be found in temperate or tropical oligotrophic lakes and estuaries. It grows best at a temperature of 23°C, a light period of 12 hours per day, and a specific light intensity and salinity. Up to 75%[85] of the dry weight of Botryococcus braunii can be long-chain hydrocarbons. Most of these hydrocarbons are botryocuccus oil that can be chemically converted into fuels. One of the major challenges with this strain of algae is the growth time, with a doubling time of 48 hours in its optimal growth environment. In August 2011, the Enomoto variety was announced by IHI with the highest yield for fuel production compared to all the algae discovered to date, with a claimed monthly growth a thousand times higher than normal strains of Botryococcus braunii[86]. It is also particularly robust. The IHI work on the Enomoto stain led to the supply of SAF for flights JL515 on 17th June 2021 between Haneda and Sapporo airports on an Airbus A350-900, and NH031 between Haneda and Osaka Itami airports on a Boeing 787-8. Those two flights were the first for aircraft equipped with fuel based on the "ASTM D7566 Annex 7". IHI Corporation works in collaboration with Chitose Laboratory on this strain.

- **Euglena:** Euglena is a microalga that combines the characteristics of plants and animals. Consequently, it grows by photosynthesis yet produces fat in its body that is suited to the production of jet fuel. Researchers in Japan were the first in the world to succeed in large-scale outdoor cultivation of euglena[87].

- **Chlorella**: In ideal conditions, cells of Chlorella multiply rapidly, requiring only carbon dioxide, water, sunlight, and a small amount of minerals to reproduce. Chlorella farming has met some challenges around the need to be grown either in artificial light or shade to produce its maximum photosynthetic efficiency, but also to be grown in carbonated water for maximum productivity, which would significantly add to the production cost. Chlorella can also be used as a cosmetic. Although promising, Chlorella has not yet been cultivated on a significant scale.

[85] Detection of the oil-producing microalga Botryococcus braunii in natural freshwater environments by targeting the hydrocarbon biosynthesis gene SSL-3 | Scientific Reports (nature.com)
[86] 2011 IHI Press Release
[87] FUELING JET AIRCRAFT WITH MICROALGAE - Innovation Japan - The Government of Japan - JapanGov -

In Japan, Botryococcus braunii[88] and Euglena[89][90] are the two main strains investigated for biofuel production, but Chlorella[91] also holds potential as it is already grown in Japan[92] for its nutrition and health properties. Those three strains can be grown and harvested in both closed and open pond systems, but, while more expensive, a closed system is preferred for a better growth rate.

1.4 Production mechanisms

Algae need sun, CO2, and nutrients to grow. In a controlled environment, some algae can grow multiple times per day, be harvested daily, and have a better yield than other uses for a given land area, such as food production. Successful harvesting techniques are highly dependent on the algae strain.
As outlined in the table below, there are two main types of algae cultivation routes, open pond system, and closed pond system.

- **Open pond system:** Open systems, such as shallow big ponds, tanks, and circular and raceway ponds, are less expensive, and easier to scale, but need a lot of land, limiting scalability. They are also more exposed to challenges such as intrusive species and predators, pathogens, etc., creating a low surface-to-volume ratio. Cells can also get stuck in the shade which can reduce growth. The low productivity of open systems makes them less suitable for commercial applications.

- **Closed pond system:** Closed systems, such as flat panels, tubes, or plastic bags, have a higher productivity, lower contamination risk and reduce evaporation, but are quite cost-intensive. They can face issues with CO2 transfer and can build up oxygen inside which kills the algae.

While closed systems are more flexible, space-efficient less weather-dependent and space-demanding, they require more cost for setup and operation. The following table provides an overview of the different risks associated with both open and closed pond systems. In Japan, Euglena[93] and IHI[94], in collaboration with Chitose Group[95], opted for open pond systems.

[88] Detection of the oil-producing microalga Botryococcus braunii in natural freshwater environments by targeting the hydrocarbon biosynthesis gene SSL-3 | Scientific Reports (nature.com)
[89] Marine Drugs | Free Full-Text | Mixotrophic Cultivation Optimization of Microalga Euglena pisciformis AEW501 for Paramylon Production (mdpi.com)
[90] Fatty Acids Extraction from Algae- Chlorella Vulgaris – IJERT
[91] Chlorella vulgaris | Powder purchase (alganex.com)
[92] Morphology, composition, production, processing and applications of Chlorella vulgaris: A review (hal.science)
[93] Algae from Japan: Energizing Population and Transportation Networks / The Government of Japan - JapanGov -
[94] Success in massive scale algae cultivation for Biofuel | 2015FY | News Articles | IHI Corporation
[95] We want to produce algae biofuel to solve the problem of energy shortage | Projects | CHITOSE GROUP (chitose-bio.com)

Table 1: Open pond versus closed system risk assessment

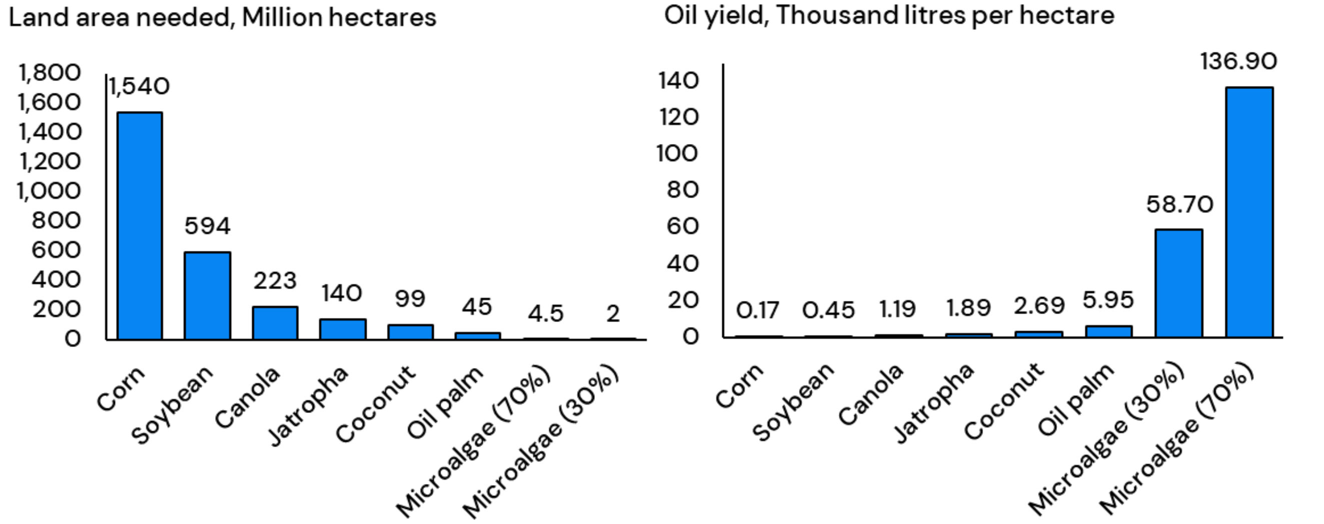
Parameter	Open pond system	Closed system
Contamination risk	🔴	🟢
Space required	🔴	🟢
Water losses	🔴	🟢
CO_2 losses	🔴	🟢
Flexibility of production	🔴	🟢
Weather dependence	🔴	🟢
Lighting sources	🟢	🟡
Maintenance requirements	🟡	🔴
Volume of production	🟢	🟡
Cost for setup	🟢	🔴

Legend	
🟢	Low risk
🟡	Medium risk
🔴	High risk

1.5 The benefits of algae cultivation

Microalgae have a high oil yield potential compared to other crops used for biofuel and also require less land area. This is particularly relevant in Japan given the extreme scarcity of useable land.

Microalgae have a significantly higher oil yield compared to other crops, with a lower land use requirement



Source: ICF Analysis, Christi, 2007.

Algae can grow quickly and efficiently throughout the year, in freshwater, seawater, brackish water or even polluted water. Production can be on degraded land and therefore does not compete with agricultural processes and could be installed to capture waste carbon dioxide feeds from industry and power stations.
The oils harvested from algae production offer organic hydrocarbons that can be refined into a variety of products such as cosmetics, plastics but also fertilizers. Co-products can be animal feed and fish food.

In 2022, India's Reliance Industries Ltd successfully developed large algae raceway ponds in their facility near Jamnagar, to convert sunshine, CO2, and seawater into bio-oil. It displayed the utilisation of catalytic hydrothermal liquefaction technology to convert algae biomass to oil. Under this process, water is used as a solvent under high temperatures and pressure to extract oil from the biomass. The benefits of this technology include direct utilisation of wet biomass without any need for drying and conversion of every organic fragment of biomass into oil and without any waste[96].

1.6 The challenges of algae cultivation

The major challenges associated with algae biofuel include high water and energy consumption, high cost of growth nutrients and biomass harvesting, and difficult oil extraction from algae cells. The energy cost of extracting oil from algae biomass is ten times higher than the energy cost of extracting soybean oil[97]. Algae can also be used to produce more profitable products than fuel, such as pharmaceutical components and organic fertilisers.

[96] Will algae biofuels become viable? (downtoearth.org.in)
[97] Will algae biofuels become viable? (downtoearth.org.in)

One of the most common problems in cultivating algae is the contamination of other micro-organisms, such as fungi, bacteria, and viruses, which can significantly decrease productivity, especially in open ponds. The production also requires significant water resources to grow the colonies and keep the liquid at specific temperatures to maximize duplication. The amount of water needed to create SAF from algae is significantly higher than most other options in development[98]. Significant quantities of fertilizer are needed to encourage photosynthesis and have an efficient algae colony growth rate. Algae production rates can vary drastically (~50%[99]) from Summer to Winter, which can be a challenge for Japan due to its variable climate.

The costs associated with production can be up to ten times compared to fossil fuel due to lack of technology maturity. The two main cost drivers that need to be improved for algae to be scalable are growth rate and lipid content. Researchers are working on ways to improve both through selective breeding and genetic modifications. To date, the production of bioenergy from microalgae is not viable as the amount of energy required during production is significantly greater than the energy derived as a product.

Outlook of algae production in Japan

1.1 Analysis of existing algae production projects

There have been few projects to date utilising these algae strands. The New Energy and Industrial Technology Development Organization (NEDO) has provided funding to several projects since 2017, aiming to demonstrate the production of SAF from microalgae. Existing algae projects in Japan are as follows:

- **IHI Corporation (in collaboration with Chitose Laboratory Corporation):** IHI Corporation is supported by the Ministry of Economy, Trade and Industry (METI) and NEDO through the "Development of Production Technologies for Biojet Fuels" project (JPY 5.18 billion[100]). They are using solar energy to culture the algae strain Enomoto (Botryococcus braunii) and focusing on improving the breeding of the strain and developing mass cultivation technology, to achieve technical improvements which can cope with open pond production. IHI Corporation established SAF production and constructed the supply chain by using its existing facility in Kagoshima city, Kagoshima prefecture, and a pilot outdoor cultivating facility in Saraburi province, Thailand. This project was planned in cooperation with relevant businesses by METI's Agency for Natural Resources and Energy and the Ministry of Land, Infrastructure, Transport and Tourism's Civil Aviation Bureau to facilitate unified efforts by SAF producers and users, to establish and promote supply chains in readiness for introducing SAF in the future[101]. By 2015, IHI succeeded in becoming the first in the world to mass cultivate Botryococcus continuously with an open-outdoor cultivation apparatus (1,500 m^2). Additionally, IHI supported the development of the ASTM D7566 Annex 7 HC-HEFA-SPK standard. As a result, two commercial flights, which were recently completed in Japan, used a blend containing renewable jet fuel created from microalgae feedstock produced by IHI[102] - JL515 from Haneda to Sapporo, 938L (11%) of SAF from IHI, of which one litre of neat SAF (0.01%), and H031 from Haneda to Itami, 988L (20%) of SAF from IHI, of which 38L of neat SAF (0.8%).

[98] 17 Advantages and Disadvantages of Algae Biofuel | FutureofWorking.com
[99] P.60 – Sustainable Aviation Fuel, Review of Technical Pathways – U.S. Department of Energy
[100] Development of Production Technologies for Biojet Fuels | NEDO
[101] Sustainable Aviation Fuel Produced from Waste Wood and Microalgae Supplied to Regular Flights | press release | NEDO
[102] Japanese Airlines Fly with Domestically Produced Sustainable Aviation Fuel (SAF) (meti.go.jp)

Based on the results of the above-outlined technological developments, IHI is aiming to commercialize bio-jet fuel production from algae by 2040.

- **Chitose Laboratory Corporation:** In April 2023, also funded by NEDO through the "Development of Production Technologies for Biojet Fuels / Development of Microalgae Base Technology \" project (~JPY 2.5 billion), Chitose Group opened the world's largest facility of microalgae production in Malaysia (open pond), "Chitose Carbon Capture Central (C4)", utilising flat-panel photo-bioreactor technology. The microalgae production of 5 hectares utilises CO2 emitted by the Sejingkat power station that will supply exhausted gas containing carbon dioxide, which is the world's first attempt[103]. The plan is to expand the farm to 100 hectares in three years, and 2,000 hectares by 2030. The location was chosen because of the ideal temperature throughout the year, the abundance of fresh water, and the state being safe from major natural disasters such as typhoons and earthquakes. It is also strategically located to access major international markets such as Japan, Taiwan, China, and Singapore. The physical construction of C4 has reached completion, and it will take about two years for the completion of the planned demonstration[104].

- **Euglena:** In 2005, Euglena succeeded in establishing the world's first outdoor mass cultivation technology for euglena microalgae. In addition to developing and selling products that include functional foods and cosmetics, Euglena has been successful in the production of biofuels. Euglena completed Japan's first demonstration plant producing renewable jet and diesel fuel in 2018, producing SAF called Susteo which contains UCO and euglena oils and fats extracted from microalgae. Recently, Euglena became Japan's first supplier that delivered domestic SAF to the hydrant system of Narita International Airport and completed Japan's first supply of SAF to the government, for a government aircraft carrying Japanese officials to the G20 intergovernmental forum in Bali[105]. Euglena is currently considering a collaborative project with Eni and PETRONAS for a commercial-scale biofuel plant in Malaysia. This plant is expected to be completed by the end of 2025 with a capacity of 12,500 barrels of biofuel per day, with microalgae considered as one of the feedstock streams by the mid-term. Although biofuels are a high-value potential for Euglena, the majority of their production today is focused on the food and cosmetics industry, due to immediate high demand.

1.2 Future Outlook

ICF developed three scenarios to determine algae oil production available in Japan; a low-scenario, medium-scenario, and high-scenario. Each scenario is defined as follows:

Table 2: Estimated scale-up production classified by type of facility

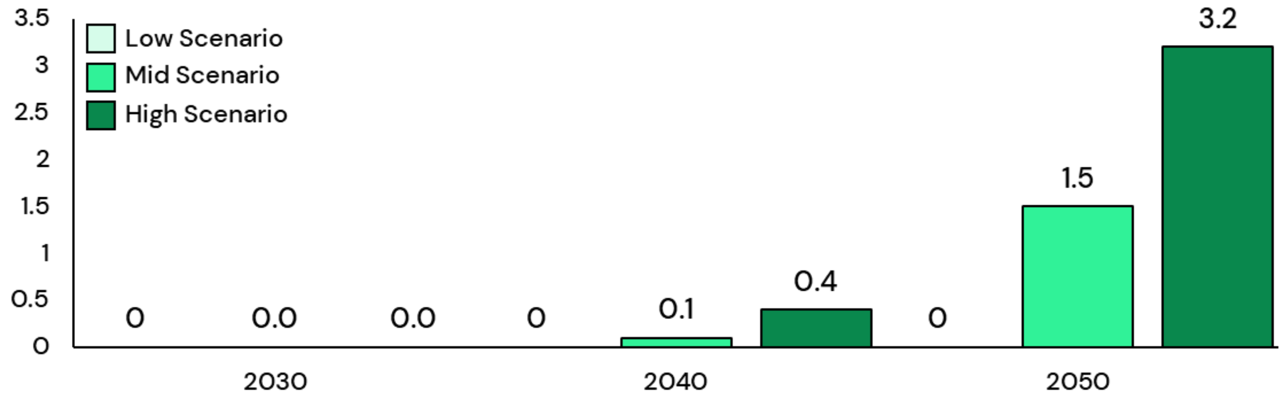
Scenario	Demonstration plant	Pilot plant	Commercial-scale
Low	No algal oil available as a feedstock in the upcoming years		
Medium	0.15 mmgpy by 2038	0.5 mmgpy by 2042	5.72 mmgpy by 2050
High	0.15 mmgpy by 2035	0.5 mmgpy by 2038	12.31 mmgpy by 2050

Based on these three scenarios, it was determined that the amount of algae available for SAF production ranges from 0 petajoules in 2030 to 3.2 petajoules in 2050.

[103] Grand Opening Held in Malaysia for the World's Largest Microalgae Production Facility | NEDO
[104] World's largest mass microalgae biomass production plant to open in Sarawak this April (theborneopost.com)
[105] Japan's Euglena supplies SAF to government aircraft | Argus Media

Long development timelines and limited production lower the opportunity for algae in the mid-term, with some consideration in the long-term

Algal oil available for SAF production, PetaJoules



Source: ICF Analysis

These estimates are relatively conservative considering the limited success to date. Given the increasing pressures to reduce emissions, achieve energy security, and preserve biodiversity, additional support could be focused on the development of algae. Unforeseen breakthroughs could result in a considerable increase above this forecast.

With six different principal climatic zones with variations in humidity and temperatures, developing commercially scaled open pond facilities would be quite challenging for Japan. Indoor facilities can be climate-controlled, but closed ponds are not expected to be profitable for decades. The same technology may be more applicable in other countries with a steady climate and land availability. While the algae production volumes outlined are limited, they may be important to develop technologies that Japanese companies could export.

Renewable electricity

1. Feedstock Description

Sustainable aviation fuel can be refined by producing hydrogen from the electrolysis of water and combining this with a source of carbon. The hydrogen and carbon can then be synthesized into fuel through several pathways, with most developers currently focusing on the Fischer-Tropsch and Methanol approaches. This is commonly called power-to-liquid SAF, and the advantages of this process are the potential for standardization and sustainability. The universal availability of electricity and carbon could allow standard designs to be used globally, which favourably compares to other SAF pathways that must be tailored to process the unique feedstocks locally available.

To be sustainable, PtL SAF must typically meet three criteria (1) the electricity must be renewable, (2) The electricity should be additional to existing demand, and (3) the carbon must be from a sustainable source. These criteria are essential because the production of PtL SAF is extremely energy intensive, with significant energy losses during the production of hydrogen and fuel synthesis. If the electricity is derived from fossil sources then the net emissions may be higher than the use of fossil jet fuel. Similarly, the electricity must be additional to ensure that its use for SAF doesn't sustain fossil generation assets that may otherwise have been decommissioned. Sustainable carbon can either be captured from a biogenic source, captured from a fossil source that would otherwise have been released into the atmosphere, or captured directly from the atmosphere.

2. Methodology

The volume of PtL SAF that can be produced in Japan will be driven by the availability of renewable electricity in addition to the grid requirement. A key constraint will be the build rate required to deliver sufficient renewable electricity to decarbonise the grid and create a surplus for PtL production. This was assessed utilising the following methodology:

1. Assessment of current production and historical trends
2. Analysis of electricity generation ambitions by the Japanese government
3. Developing an electricity forecast
4. Assessment of potential growth for low-carbon electricity
5. Conducting a supply analysis

3. Assessment

Current production and historical trends

Primary energy consumption peaked in Japan in 2005, and extensive energy efficiency efforts have driven a gradual decrease at an average of -1.5% per year through 2021[106]. Electrical demand has similarly decreased, although at a slower rate of -1.04% as the energy efficiency efforts were slightly offset by the increasing electrification of cars, heating, and other end-use sectors[107].

In 2021, a total of 919 TWh of electricity was generated, of which 77.5% used fossil fuels (32% coal, 42% Natural gas, 3.5% other), and 22.5% used low-carbon fuels (19.5% Renewables, 3% Nuclear). Over the past decade, wind, solar, and geothermal have been the fastest-growing generation sources, from 3% in 2012 to 13% in 2021. Nuclear has also recovered very gradually since the shutdowns following the great earthquake and accident at Fukushima Daiichi, growing from 2% to 6% over the same period. As of 2021, 17 reactors are awaiting approval to restart, potentially allowing nuclear to return to a more central role in the Japanese energy portfolio[108]. As renewables and nuclear have had a growing role and overall demand has declined, a small amount of production has been phased out over the last decade, primarily from oil.

[106] BP. (2022). *bp Statistical Review of World Energy*. BP.
[107] 6th SEP METI. (2021). *6th Strategic Energy Plan.* https://www.enecho.meti.go.jp/category/others/basic_plan/pdf/strategic_energy_plan.pdf: METI.
[108] U.S. Department of Energy. (2023). Country Analysis Brief: Japan. https://www.eia.gov/international/content/analysis/countries_long/Japan/japan.pdf: U.S. Department of Energy

Electricity generation ambitions

Japan has an established S+3E framework of energy goals, covering Safety, Energy Security, Environment, and Economic efficiency. The 6th Strategic Energy Plan published by METI in October 2021 set ambitious 2030 targets for each of these metrics, with the Energy self-sufficiency rate increasing to 30%, energy-related CO2 reducing by 45% compared to a 2013 baseline, and an average electricity cost of 9.9-10.2 yen/kWh.

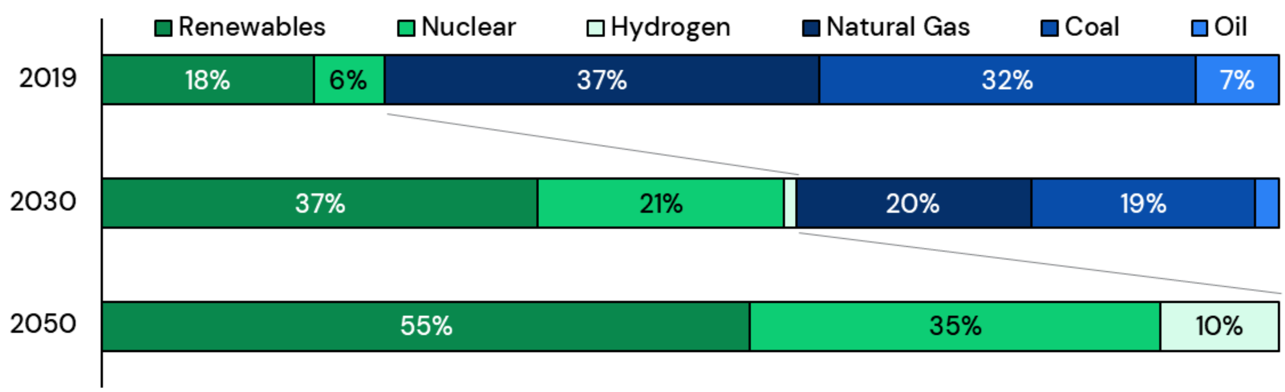
These targets represent a rachet in environmental ambitions compared to the 5th SEP, which set a 2030 decarbonisation target of 25% reduction vs 2013. The updated target sets Japan on a practical trajectory towards the 2050 carbon neutrality goal, although considerable challenges must still be overcome[109].

The initiatives to achieve these targets span demand reduction, growth in renewables, recovery of nuclear generation, and decarbonising existing fossil infrastructure. Demand reduction includes the use of the Benchmark program to reduce industrial emissions, updated commercial and residential building efficiency standards, and promotion of electric vehicles. Renewables are planned to increase to 36% - 38% of electricity consumption by 2030, and nuclear power to recover to 2010 levels, equivalent to 20-22% of overall production. Existing infrastructure is to be initially decarbonised through carbon capture and co-firing hydrogen or ammonia.

A further ramp is required to achieve the 2050 carbon neutrality target. Renewable energies must deliver 50%-60% of total generation, nuclear should increase to 30-40% and co-fired hydrogen or ammonia power will account 2050 for 10% of total electricity production.

Rapid growth of renewables and nuclear allows fossil fuels to be phased-out

The forecast Japanese energy mix



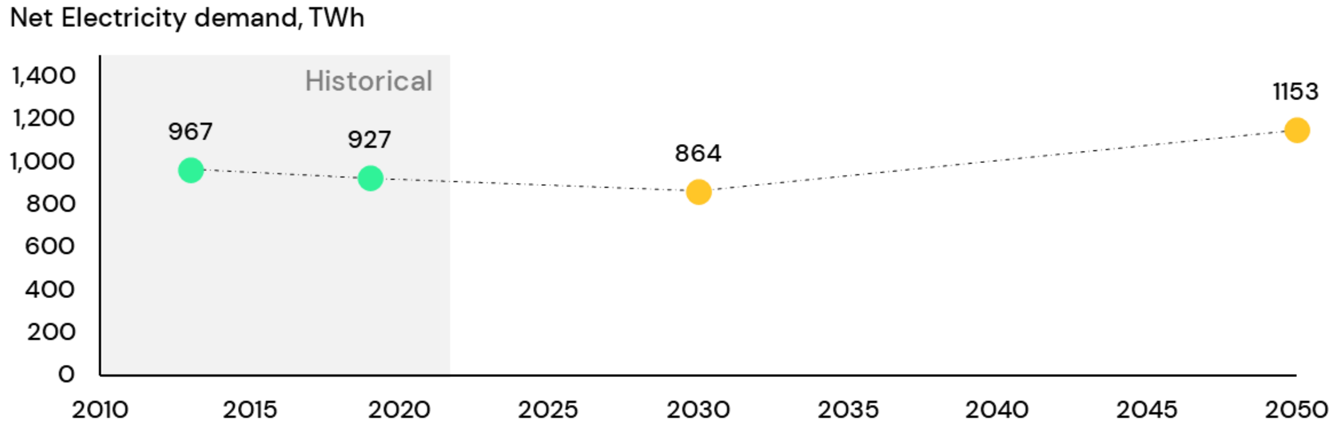
Source: METI, EU-Japan Centre for Industrial Cooperation, Japan's 2050 goal: A carbon-neutral society

[109] METI Green Growth. (2021). Green Growth Strategy Through Achieving Carbon Neutrality in 2050. https://www.meti.go.jp/english/policy/energy_environment/global_warming/ggs2050/pdf/ggs_full_en1013.pdf: Ministry of Economy, Trade and Industry .

Electricity forecast

METI forecasts electricity demand at 864 TWh in 2030 but provides only qualitative indications for 2050. The International Energy Agency provides two longer-term scenarios, the Stated Policy Scenario (STEPS) and the Announced Pledge Scenario (APS)[110]. The APS represents the more ambitious scenario with an implicit assumption that additional initiatives accelerate the Japanese decarbonisation trajectory to align with the announced pledges and targets. This matches the ambition of this analysis and will be used for the remainder of the calculations. IEA forecasts a 1,153 TWh net electricity demand in 2050, equivalent to 189 additional TWh compared to METI projections in 2030.

Japan's electricity demand is forecast to rebound as end-use sectors decarbonise

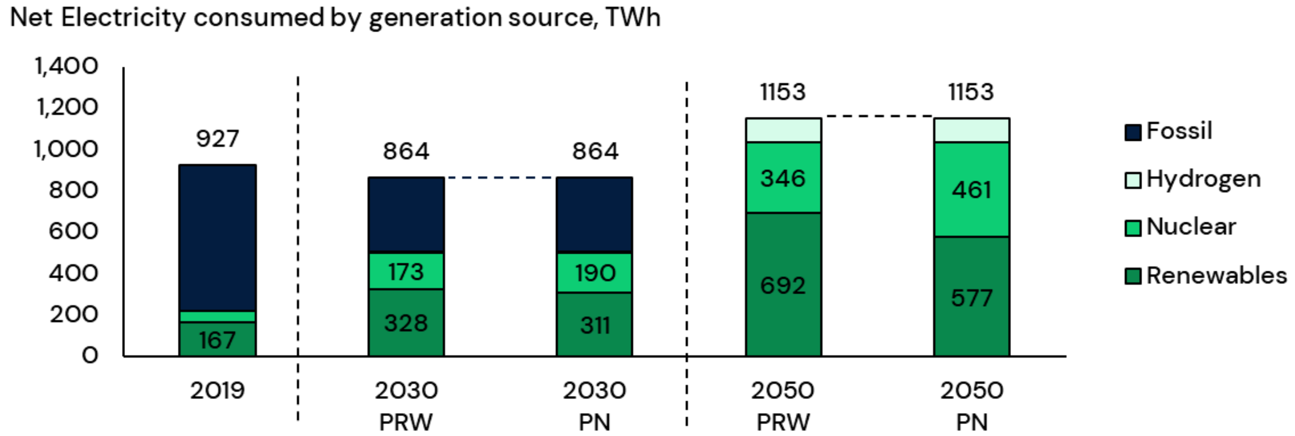


Source: Historical from METI, Forecast from IEA World Energy Outlook, aligned to the APS scenario

To reach the forecasted demand, METI provides a range of expected percentages per technology. Two key scenarios are (1) pushed nuclear and (2) pushed renewables, which reflect scenarios where either nuclear or other renewables (solar, wind and geothermal) see the greatest acceleration. The level of demand (864 TWh in 2030 and 1153 TWh in 2050) and the percentage of low-carbon energy (59% in 2030 and 100% in 2050) are the same in both scenarios. Combining the energy mix and the electricity demand provides a range of demands by the power source for 2030 and 2050.

[110] IEA. (2022). World Energy Outlook 2022. https://iea.blob.core.windows.net/assets/830fe099-5530-48f2-a7c1-11f35d510983/WorldEnergyOutlook2022.pdf: International Energy Agency.

Decarbonising and growing supply requires a rapid growth in renewables



Source: ICF analysis. PRW = Pushed Renewables scenario, PN = Pushed Nuclear scenario

While the macro forecast does not mention an energy allocation for SAF production, the 2023 revised Hydrogen Strategy[111] mentions the use of synthetic fuel from hydrogen-based technologies. Therefore, some hydrogen production may be included within the electricity projections, although it is likely that the volumes will be incremental and will require additional generation capacity.

Potential growth for low-carbon electricity

The target set by the Japanese government implies relatively high growth rates over the coming decades, especially through 2030. Double-digit CAGR for nuclear power sources until 2030 is feasible because it is a matter of restarting existing facilities, and as of 2023, 17 reactors are awaiting approval to restart.

Table 1: Japanese government set electricity targets

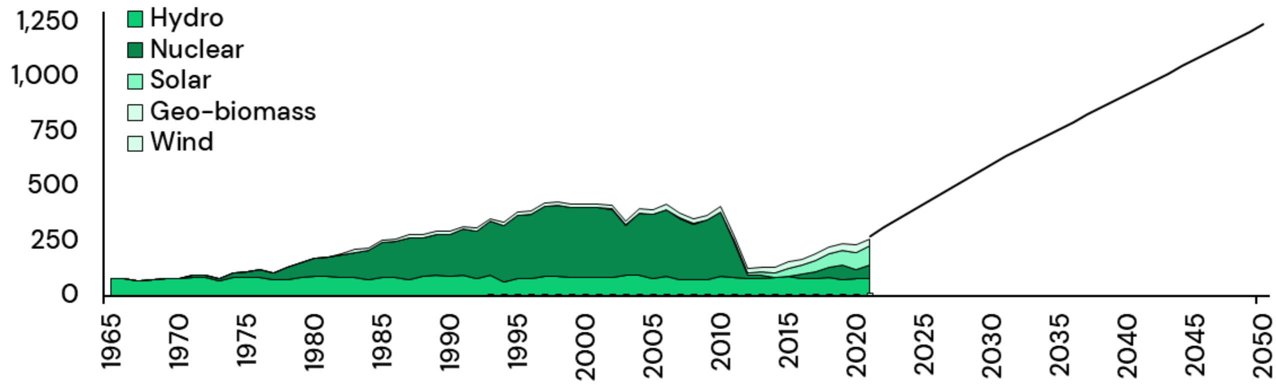
CAGR vs 2019	2013-2019	2030		2050	
		PRW	PN	PRW	PN
Renewables	33.90%	6.30%	5.80%	4.70%	4.10%
Nuclear		10.90%	11.80%	6.10%	7.10%
Total		**7.80%**		**5.40%**	

From a comparison point, these CAGRs are lower than the 14.3% growth achieved by renewables in Japan between 2011 to 2021, and the 9.0% achieved in OECD countries over the same period. The growth in renewables aligns with the global trend, with solar and wind expected to provide more than 80% of additional capacity from 2022 to 2050.

[111] REI. (2017). Basic Hydrogen Strategy. https://policy.asiapacificenergy.org/sites/default/files/Basic%20Hydrogen%20Strategy%20%28EN%29.pdf: Ministerial Council on Renewable Energy.

Historical supply of low-carbon power has grown rapidly, particularly nuclear (1980+) and solar (2010+)

Historical and Forecast Electricity Generation by Energy Sources, TWh

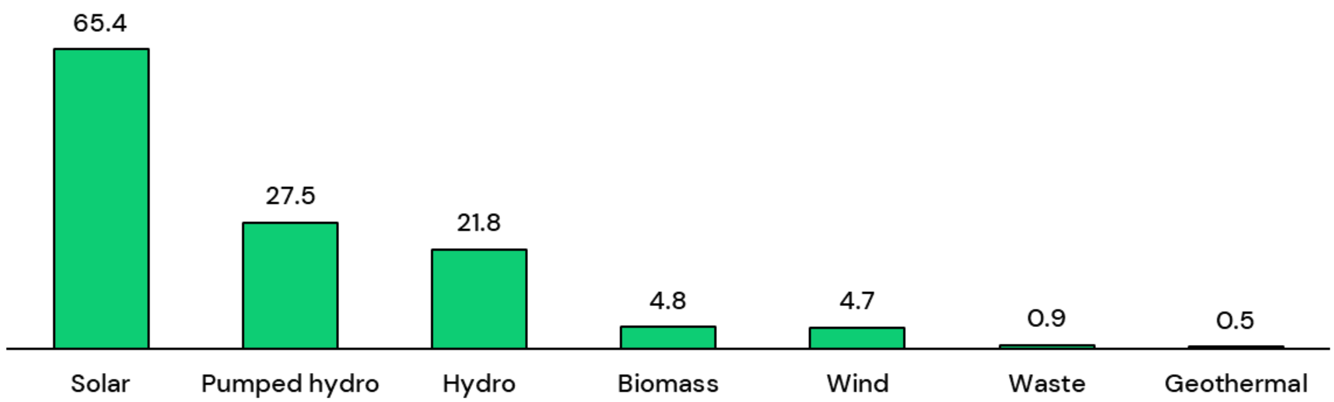


Source: BP Statistical Review, ICF Analysis

To achieve the 2050 electricity generation objectives, the Japanese government established specific targets for the installed power generation capacity of each renewable energy source. The 6th Strategic Energy Plan outlines an increase in the capacity of solar photovoltaic power generation and wind power generation to be respectively 20 times and 11 times between 2021 and 2050[112]. Current projects include the construction of 10 GW offshore wind capacity by 2030, and between 35 GW and 45 GW by 2040.

Installed renewable electricity is dominated by solar, supported by hydropower

Japan 2021 Renewable energy generation capacity, GW installed capacity



Source: Organization for Cross-regional Coordination of Transmission Operators, 2022 Aggregation of Electricity Supply plan for FY2022

[112] OCCTO. (2022). Annual Report FY 2022. https://www.occto.or.jp/en/information_disclosure/annual_report/files/230803_OCCTO_annualreport_2022.pdf: Organization for Cross-regional Coordination of Transmission Operators.

The growth of renewables was significantly catalyzed by the closure of all nuclear generation in 2011, and the parallel maturing of technologies that made solar and wind increasingly cost-competitive. The targets require growth across all generation technologies, with diversification necessary to overcome constraints in land, weather, and generation variability.

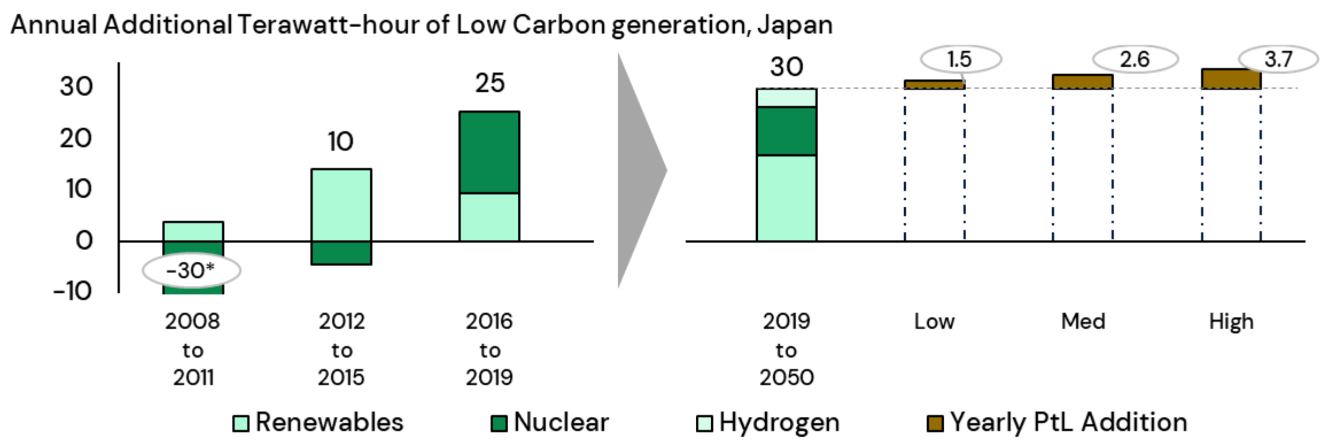
Supply analysis

Aviation will need significant renewable electricity to decarbonise and produce SAF. While plentiful wind and solar radiation mean renewable energy technologies are not constrained by feedstock, practical factors such as space, funding, and build rates will limit the amount available for the production of PtL SAF. To ensure the sustainability of the PtL produced, this analysis assumed that all renewable electricity used for PtL production was additional to the amount required to decarbonise grid demand. Three scenarios were developed to illustrate a range of growth scenarios, representing ambitious but realistic scenarios, particularly if SAF production can act as a demand-pull factor to create a reliable and economically viable market that attracts the required resources. The specific values were calculated to offer a realistic range in terms of compound growth, absolute growth, and absolute numbers:

- **Low**: an additional +4% of total electricity production in 2050 will be available for SAF production, equivalent to +45TWh
- **Mid**: an additional +7% of total electricity production in 2050 will be available for SAF production, equivalent to +80TWh
- **High**: an additional +10% of total electricity production in 2050 will be available for SAF production, equivalent to +115TWh

The amount required to meet these three scenarios is shown below, this is in addition to the 30 TWh required to decarbonise the grid demand.

Annual growth in low-carbon electricity for the three PtL scenarios

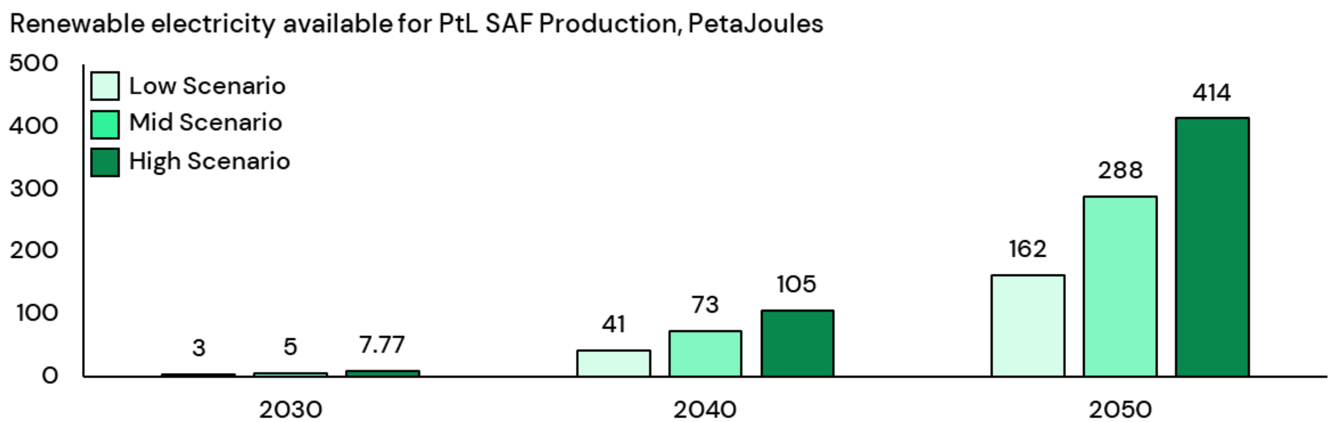


Source: ICF Analysis.

These three scenarios allow the calculation of the required growth in renewable energy to provide an excess for SAF production. Without SAF, the 2019-2050 CAGR for renewable energy would be 5.4%. Adding the SAF scenario gives a CAGR requirement between 5.6% and 5.8% over the same period. This is below the expected growth for 2030 and below the historic growth for OECD countries. In absolute terms, decarbonising the grid (with no PtL) would require Japan to increase its low-carbon electricity generation by 30 TWh each year from 2019 to 2050. The additional requirement for PtL would increase the growth rate by +1.5 to +3.7 additional TWh per year.

An exponential growth rate was assumed, to align with the historic deployment dynamics, and the increasing potential to deploy as equipment, infrastructure, and workforce are scaled. The final values were then converted into petajoules to facilitate comparison to the other feedstock categories, as shown below.

Forecast of 160-410 PJ of renewable electricity for PtL SAF production in 2050



Source: ICF Analysis

Recycled Carbon

1. Feedstock Description

In the journey to aviation decarbonisation, the industry is exploring all potential resources to produce SAF. PtL production approach uses CO2, and low-carbon hydrogen as feedstocks to refine sustainable aviation fuel. While energy consumption is the main cost driver and constraint, the availability of CO2 is also crucial. This section focuses on the opportunity to capture and re-use CO2 from various sources, including industrial emissions, reducing the volume of CO2 that must be captured from the atmosphere.

Global CO2 emissions are unfortunately abundant, with numerous industrial processes generating it as a waste. Capturing the CO2 directly at its industrial source is called Point Source CO2 Capture (PSC), and contrasts with Direct Air Capture (DAC) systems that can harvest CO2 from the atmosphere.

The Japanese government aims to significantly reduce its greenhouse gas (GHG) emissions through new technologies and improved operations, with carbon capture technologies used to address the residual emissions. The Basic Policy for Realization of GX (Green Transformation) [113] was approved in 2023 and stated an objective of 120 to 240 Mtpa of CO2 captured in 2050[114]. As highlighted by the Research Institute of Innovative Technology for the Earth (RITE) the Japanese demand for Carbon Capture, Utilisation and Storage (CCUS) may be higher than the government's current target[115].

The utilisation of CO2 for PtL SAF aligns with global efforts to reduce aviation emissions and transition to greener energy solutions, contributing to a more sustainable aviation sector.

2. Methodology

The following factors and methodology were used to assess the potential of SAF made from CO2 in Japan:

1. Assessment of current and historical CO2 emissions in Japan
2. Determining the potential for point source capture (PSC) technologies to transition to direct air capture (DAC)
3. Sectoral deep dive into industry sectors for PSC technologies
4. Assessment of CO2 availability for aviation

3. Assessment

Producing SAF SAF from non-biological feedstock

1.1 Current and historical emissions in Japan

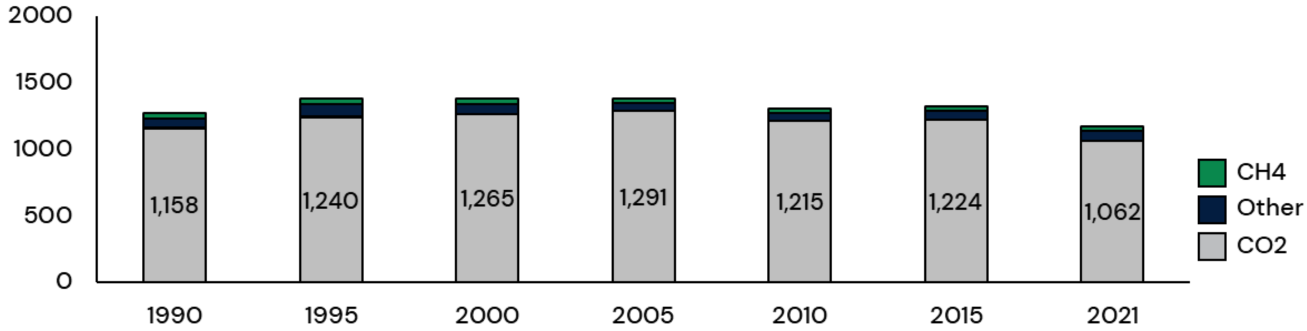
The National Greenhouse Gas Inventory published yearly by the Ministry of Environment of Japan provides a summary of the national trends in GHG emissions since 1990[116]. The historical Analysis relies on the National Greenhouse Gas (NGG) inventory report from 2022.

Japan emitted 1,168 Mt of $CO2_{eq}$ in FY2021, which corresponds to a 9.6% decrease against FY1990. Pure CO2 emissions accounted for 91% of total GHG Emissions in Japan in FY2021. That same year, CO2 removals achieved through Land-Use, Land-Use Change and Forestry (LULUCF) were equivalent to 4.5% of total GHG emissions or 52.2 Mt CO2eq. Total Japanese GHG emissions peaked in 2013 and have gradually decreased since.

[113] https://www.meti.go.jp/press/2022/02/20230210002/20230210002_1.pdf
[114] https://www.meti.go.jp/english/press/2023/0613_001.html
[115] https://www.rite.or.jp/system/en/global-warming-ouyou/download-data/E-202106analysisaddver.pdf
[116] https://cger.nies.go.jp/publications/report/i164/i164.pdf

Japan's GHG emissions represented 1,118Mt CO_{2eq} in 2021 amongst which 94% are direct CO_2 emissions

Historical net GHG emissions and removals, Mt CO_{2eq} FY1990-FY2021



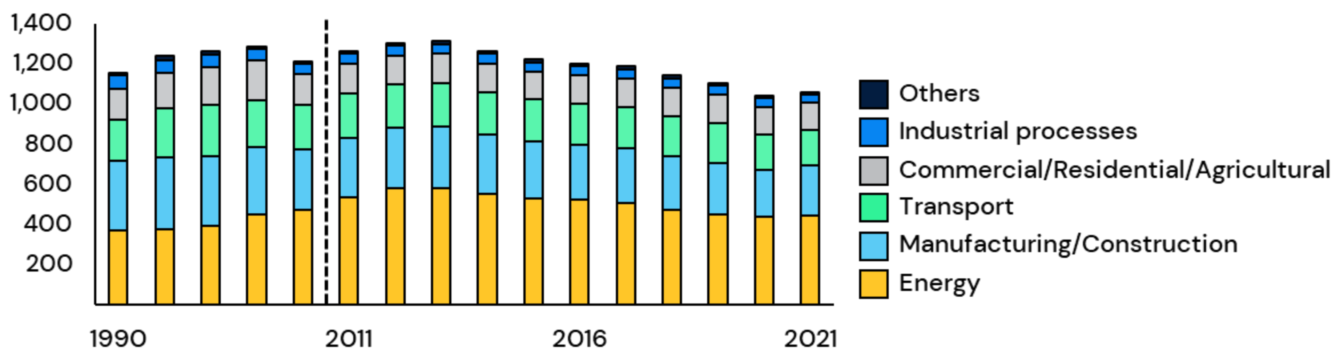
Source: National Greenhouse Gas Inventory Report of JAPAN 2023

Methane (CH4), Nitrogen (N2O), and Hydrofluorocarbon (HFC) accounted for almost 95% of the non-CO2 GHG emissions since FY1990. These gases decreased rapidly to reach 106 Mt CO2eq released in FY2021. Only Hydrofluorocarbon (HFC) (waste gas from air conditioning) increased its emissions, growing by 236% since CY1990.

CO2 emissions account for most of the country's GHG emissions. The breakdown of these emissions highlights the significant impact of fossil fuel combustion on total CO2 emissions, driving 94.6% in FY 2021 (the remainder from land-use change and smaller sources). Breaking down the fossil fuel contribution, the energy sector emitted 444 Mt in 2021 (42%), followed by 250 Mt from manufacturing and construction (23.5%), 178 Mt from transportation (16.8%) and 135 Mt from other sectors (12.8%)(1).

All sectors of the Japanese economy have started to decarbonise

Historical net GHG emissions by industry in Mt CO2eq FY1990-FY2021



Source: National Greenhouse Gas Inventory Report of JAPAN 2023

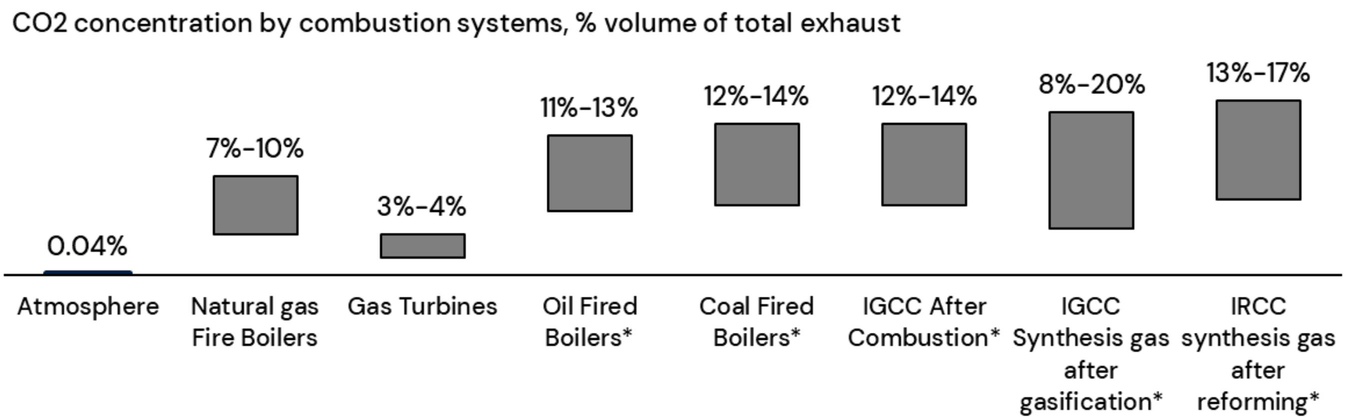
The Fukushima Daiichi nuclear disaster in 2011 served as a watershed moment for Japan's energy sector by prompting a significant reevaluation of the country's energy policies, particularly its heavy reliance on nuclear power. In response, Japan embarked on a journey to diversify its energy mix, invest in renewables, and enhance safety measures, marking a transformative shift in its energy landscape. Consequently, the energy sector experienced the largest drop in CO2 emissions since 2013 but remains at a higher level than FY1990.

Not all CO2 emissions are economical to capture

The economic viability of Power-to-Liquid SAF is directly correlated to the provision of feedstocks and consequently to the cost of Carbon Capture. Lowering the cost of carbon capture is key for PtL SAF to scale up and become competitive compared to fossil fuel. Focusing on sources with higher concentrations of CO2 will be important.

CO2 in the atmosphere was around 415.7 ppm in 2021 according to the Japanese Meteorological Agency[117], representing a 0.04% CO2 composition. Heavy industrial sources are significantly more concentrated, with industrial combustion systems between 75 and 425 times more concentrated in CO2 than the atmosphere[118].

Industrial combustion systems exhausts are between 75 to 425 times more concentrated in CO_2 than the atmosphere

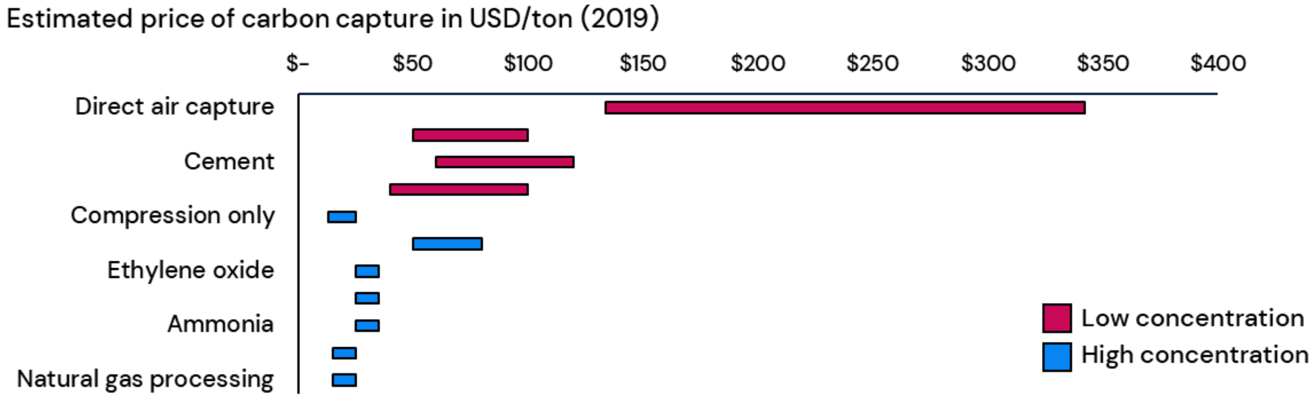


Source: ICF analysis

The higher the concentration, the easier it is to capture and separate the carbon from the other particulates. Consequently, the cost of carbon capture in high-concentration industries (PSC) is lower than DAC. The International Energy Agency estimates the price of DAC to be two to seven times higher than PSC[119].

[117] https://ds.data.jma.go.jp/ghg/kanshi/ghgp/co2_e.html
[118] https://www.researchgate.net/publication/242237727_Comparison_of_solvents_for_post-combustion_capture_of_CO_2_by_chemical_absorption
[119] https://www.iea.org/data-and-statistics/charts/levelised-cost-of-co2-capture-by-sector-and-initial-co2-concentration-2019

Low concentration carbon sources generally costs more to capture than high concentration sources



Source: IEA, Levelised cost of CO2 capture by sector and initial CO2 concentration, 2019

The analysis of available CO2 at point sources in Japan with high concentrations is essential to assess the CO2 availability for PtL as it appears to be the cheapest way to capture CO2. The remainder of CO2 required to fulfill the aviation market demand in PtL SAF will therefore be sourced from DAC with more expensive technologies.

Potential for PSC, sectoral deep dive, and government target

While considering the industrial sectors with high potential for CCUS technologies, it is important to recognize that these industries will grow and start their decarbonisation journey. Most of the following industries are challenging to decarbonise because no alternative method exists and therefore are strong candidates for CCUS. Several industries were not included in this analysis due to the lack of available data (i.e. chemical industry).

1.1 Cement Industry

17 cement producers spread across 30 plants are present in Japan, mainly in mountainous areas where limestone mines are located[120]. The country can produce 54 Mtpa of clinker which is an intermediary product in the production of cement. The long-term vision for the cement industry toward a decarbonised society is expecting a cement demand between 34 and 42 Mtpa[121]. Considering the cement emission intensity being 763 kgCO2/t-cement, it means that the cement industry could be capable of capturing between 25.9 and 32 Mtpa if we capture the total amount of emitted gas.

1.2 Iron and Steel

Emissions from the steel industry account for 48% of Japan's industrial CO2 emissions and 13% of the country's total energy-related CO2 emissions. The average equipment lifetime is 25 years amongst which half of them will reach their operational the end of their operational lifetime by 2030[122].

[120] https://www.jcassoc.or.jp/cement/2eng/e_02.html
[121] https://www.meti.go.jp/policy/energy_environment/global_warming/transition/transition_finance_technology_roadmap_cement_eng.pdf
[122] https://www.renewable-ei.org/pdfdownload/activities/REI_greensteelEN2023.pdf

The country's crude steel production was approximately 100 Mt in 2022[123]. The Japanese government forecasts a demand of 90 Mtpa in 2030 and a further drop in 2050 due to population decline and falling exports. A study by the World Economic Forum (WEF) and the government aligns on projections for crude steel demand to be 75 Mtpa in 2050[124]. The Renewable Energy Institute (REI) combined all these assumptions as well as some reduction targets to end up with the final figure for the CCS requirement of 47 Mt in 2050.

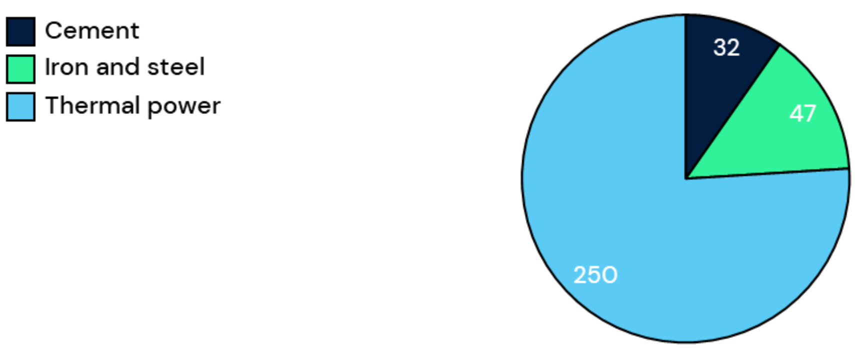
1.3 Thermal Power

The Japanese government set ambitious targets to reach net zero by 2050, especially for its power supply. While it will mostly rely on the development of renewable energies, (50-60%) and hydrogen/ammonia (10%), the remaining 30-40% will be covered between nuclear and thermal power with CCUS.

Thermal power, including coal and natural gas, has been a reliable source of baseload power for decades, providing a consistent and essential energy supply but its decarbonisation is a challenge that requires the use of carbon capture technologies as these generation sources released highly concentrated CO2 exhausts.
As explained by the RITE (3) and the REI[125], the CO2 capture demand for thermal power stations is equivalent to 250 Mtpa in 2050. This exceeds the upper scenario set by the Japanese government of 240 Mt, leaving minimal potential for industrial decarbonisation through CCS.

Forecasts estimate that Japan will need to capture over 300 Mt of CO2 in 2050 to reach net zero

Carbon capture by industry projections in 2050 in Mt



Source: ICF Analysis, RITE, WEF, REI

[123] https://www.jisf.or.jp/en/statistics/production/index.html
[124] https://www3.weforum.org/docs/WEF_Industrial_Decarbonisation_in_Japan_2023.pdf
[125] https://www.renewable-ei.org/pdfdownload/activities/REI-CCSbottlenecks-risks_EN.pdf

Japan roadmap and revisions

1.1 Existing carbon capture and storage project in Japan

The first pilot CO2 storage project dates to the 2000s when 10,000t CO2 were injected into a saline aquifer between 2003-2005. The Tomokomai project is currently the first full-scale operational CCS project which managed to store 300,000t CO2 in 2019.

To reach 46% GHG emissions reduction by 2030 and ideally a carbon neutrality society in 2050, numerous CCS projects were initiated and selected to provide approximately 6 to 12 Mtpa CO2 by 2030[126]. The Japanese Organization for Metals and Energy Security (JOGMEC) selected seven projects. As previously mentioned, the nature of the CCS projects is linked to heavy industrial processes with high concentrations of CO2 emissions. In addition to the Basic Policy for Realization of GX, the government indicates that it will support the above-advanced project as a role model for developing the business environment.

The Japanese government's projections aim at capturing 120 to 240 Mtpa of CO2 through similar technologies by 2050, which would require growing domestic carbon capture capacity by 16% every year from 2030 to 2050. This figure was calculated by METI by multiplying the global CO_2 capture and storage volume under the IEA's three energy scenarios by Japan's current share of global CO_2 emissions (3.3%).

Table 1: List of projects selected to implement CCS technology in Japan in 2050

	Companies	Area of CO2 Storage	CO2 Storage Mtpa	CO2 Emission Sources
Tomakomai Area CCS	Japan Petroleum Exploration Com Ltd. (JAPEX), Idemitsu Kosan Co.,Ltd., Hokkaido Electric Power Co.,Inc.	Tomakomai Area (Oil and gas field or saline aquifer)	1.5	Oil refinery, electric power plant in the Tomakomai Area
Tohoku Region West Coast CCS	ITOCHU Corporation, Nippon Steel Corporation, Taiheiyo Cement Corporation, Mitsubishi Heavy Industries, Ltd., ITOCHU Oil Exploration Co., Ltd., INPEX Corporation, Taisei Corporation	Tohoku west coast offshore region, etc. (Offshore saline aquifer)	2	Wide-area CO2 emissions in Japan Steel plants, cement plants and local emitters near the CO2 storage

[126] https://www.jogmec.go.jp/news/release/content/300384254.pdf

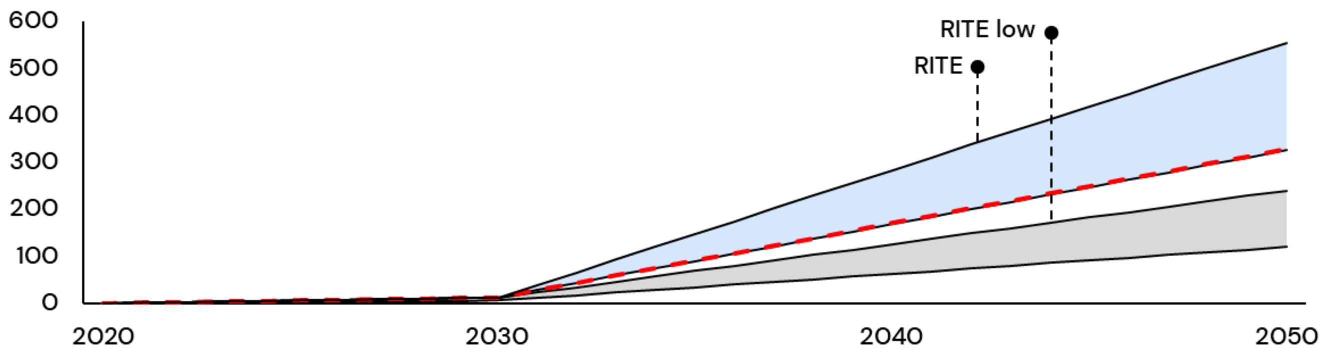
East Niigata Area CCS	Japan Petroleum Exploration Com Ltd. （JAPEX） , Tohoku Electric Power Co., Inc., Mitsubishi Gas Chemical Company, Inc., Hokuetsu Corporation, Nomura Research Institute, Ltd.	Niigata Prefecture (Oil and gas field)	1.5	Chemical plants, pulp mills, electric power plants in Niigata Prefecture
Metropolitan Area CCS	INPEX Corporation, Nippon Steel Corporation, Kanto Natural Gas Development Co., Ltd.	Metropolitan areas, etc. (Offshore saline aquifer)	1	Multiple industries including steel plants in metropolitan areas
Northern to Western Kyushu Offshore CCS	ENEOS Corporation, JX Nippon Oil & Gas Exploration Corporation, Electric Power Development Co., Ltd. (J-POWER)	Offshore northern to western Kyushu (Offshore saline aquifer)	3	CO_2 emissions in the Setouchi/ Kyushu regions Oil refineries, electric power plants in West Japan
Offshore Malay CCS	Mitsui & Co., Ltd.	Offshore the east coast of the Malay Peninsula in Malaysia （Offshore depleted oil and gas field, saline aquifer）	2	Multiple industries including chemicals/oil refineries in the Kinki/ Kyushu regions, etc.
Oceania CCS	Mitsubishi Corporation, Nippon Steel Corporation, ExxonMobil Asia Pacific Pte. Ltd.	Oceania (Offshore depleted oil and gas field, saline aquifer)	2	Multiple industries including steel plants in the Chubu region（Nagoya, Yokkaichi)

Scenario development

By adding up all estimates from the sector deep dive section, around 330 Mt of CO_2 is required to be captured to reach net zero in 2050. While the targets set by the government are slightly lower (120 and 240 Mtpa), RITE estimates that CCS volumes are likely to exceed the targets and capture between 326 and 555 Mtpa in 2050.

RITE estimates in 2050 are almost double the Japanese government, while ICF aligns on the low scenario from RITE

CCS projections in 2050 comparison in Mtpa of CO2 captured



Source: METI, JOGMEC, RITE, ICF Analysis

Availability of captured carbon for SAF production

To produce 1 tonne of PtL jet fuel, approximately 4.3 tonnes of CO2 are needed[127]. This means with the targeted CO2 captured from PSC (120 Mt to 240 Mt), Japan could produce as much as 27.9 - 55.8 Mt of SAF annually, which is substantially greater than the 23 Mt of fossil kerosene consumed every year in Japan today[128]. However, not all of this PSC CO2 will be available for PtL production. Significant volumes may need to be permanently removed rather than stored, with other constraints limiting the PtL potential.

PSC carbon still represents the addition of CO2 to the atmosphere; therefore the industry will need to transition to DAC over the mid/long term. DAC technology captures carbon dioxide directly from the atmosphere. DAC is an energy-intensive technology and is comparatively expensive. DAC systems also require open space for installation, albeit relatively limited, with expectations of reductions as technology advances.

[127] https://www3.weforum.org/docs/WEF_UAE_Power_to_Liquid_Roadmap_2022.pdf

[128] https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2022-full-report.pdf

4 Import and export opportunity

Import opportunity

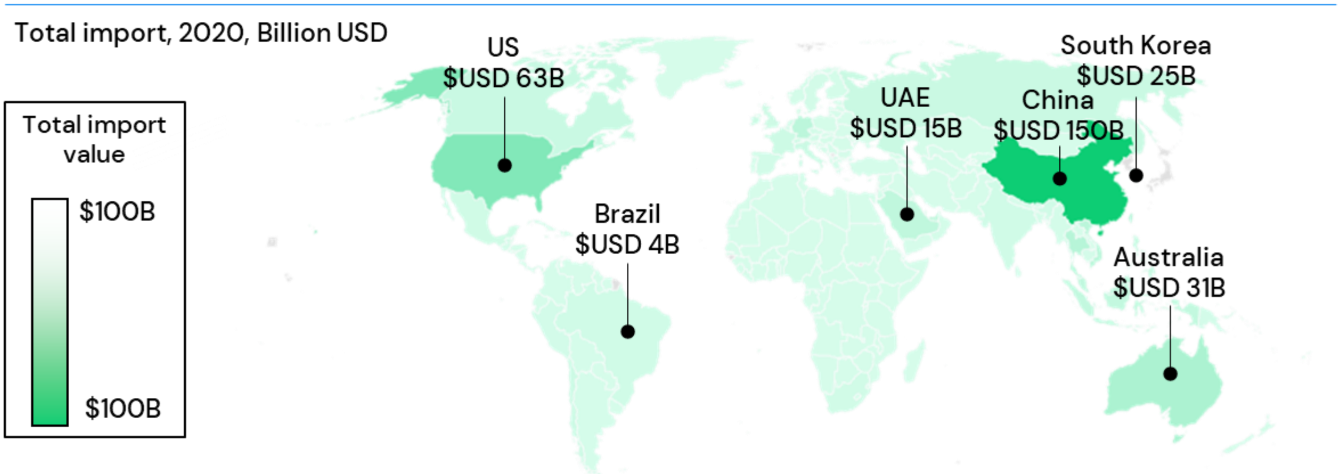
In addition to the domestic opportunities, Japan may be able to import considerable feedstock, intermediaries, and SAF to decarbonise the aviation sector. This has precedence in other industries, with significant volumes of wood chips and PKS imported for power generation, and ongoing discussions to import bio-intermediaries such as ethanol from sugarcane or corn to decarbonise the road and aviation sectors. All SAF currently used in Japan is currently imported, and with the growth of SAF capacity in Singapore, the US, and other countries, there may be potential to increase imports.

Domestic production offers greater energy security and ensures that the job creation and investment are retained within Japan. However, limited land, feedstocks, and labour may increase the price point for domestic production vs imports, and the equilibrium will be driven by policy and economics. This sector aims to illustrate the opportunity for imports, and the advantages and challenges to access global feedstock, bio-intermediary, and SAF markets.

1. Assessment of Japan's reliance on imports

In 2021, Japan had the third-largest economy in the world in terms of GDP, and the fourth in both total exports and imports[129]. The majority of imports to Japan are crude oil ($54.9 billion), petroleum gas ($40.2 billion), integrated circuits ($22.7 billion), coal ($22.2 billion), and refined petroleum ($18.1 billion), importing mostly from China, the United States, Australia, China, and South Korea.

Japan's economy is heavily dependent on imports, with majority of imports coming from China and the US



Source: The Observatory of Economic Complexity (OEC)

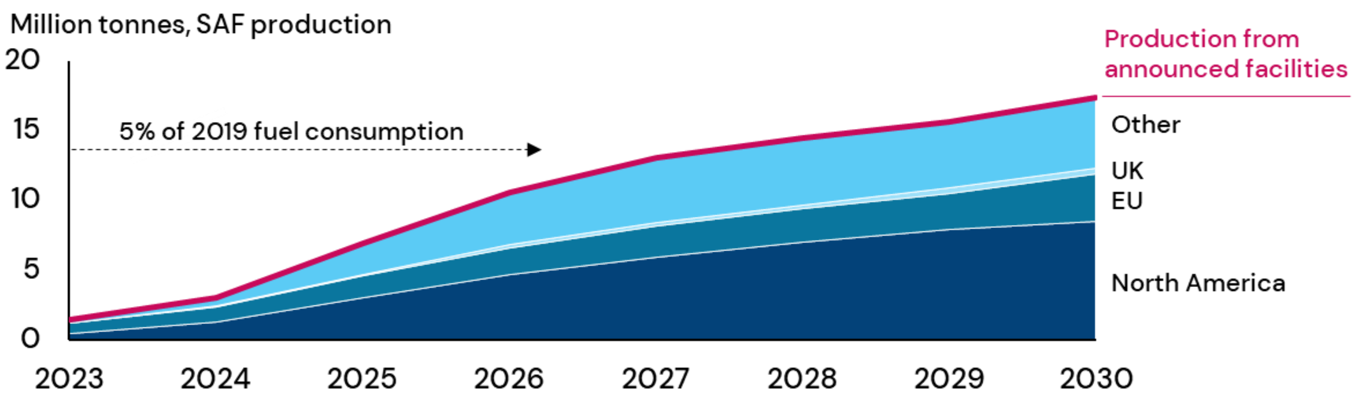
[129] https://wits.worldbank.org/CountryProfile/en/Country/JPN/Year/LTST/Summarytext

Japan is heavily dependent on imported crude oil and liquefied natural gas, with only very small volumes of domestic production. In 2021, Japan was the 5th highest consumer of oil in the world, relying on imports to meet 97% of demand[130]. This reliance shapes trade policies and international relations, highlighting the balance between self-sufficiency and global integration.

2. Global SAF market dynamics and influence on imports

The global SAF market is currently equivalent to less than 0.1% of jet fuel consumption, with c. 34,000 tonnes consumed in 2020. Meeting the industry ambition of net zero by 2050 will require c. 400 million tonnes of SAF, equivalent to a scale-up of almost 8,000 times in just three decades. While aviation is a global industry, announced SAF capacity is highly concentrated in just a few regions, with almost 50% in the US, and 20% in the EU, with the UK and the rest of the world contributing the remainder.

North America is leading SAF production with an estimated 50% share, followed by the EU at almost 20%



Source: ICF tracking of public announcements of SAF market developments

A significant number of additional facilities are under construction, using a variety of technologies, feedstocks, and approaches. As these come online over the next few years, supply will rapidly increase, with almost 2 million tonnes estimated to be added every year before 2030.

A range of existing and potential policies aim to stimulate the industry. For example, complying with the proposed ReFuel EU mandate will require airlines to uplift c. 2 million tonnes of SAF by 2030, and the UK recently finished a consultation on a SAF mandate that would stimulate production to deliver a 10% emissions reduction by 2030 (requiring c. 1.2 million tonnes). The US already has several policies in place and recently approved the Inflation Reduction Act (IRA), which contains several policies to stimulate low-carbon energy and fuel production. The global CORSIA scheme also provides some support for SAF consumption by international airlines.

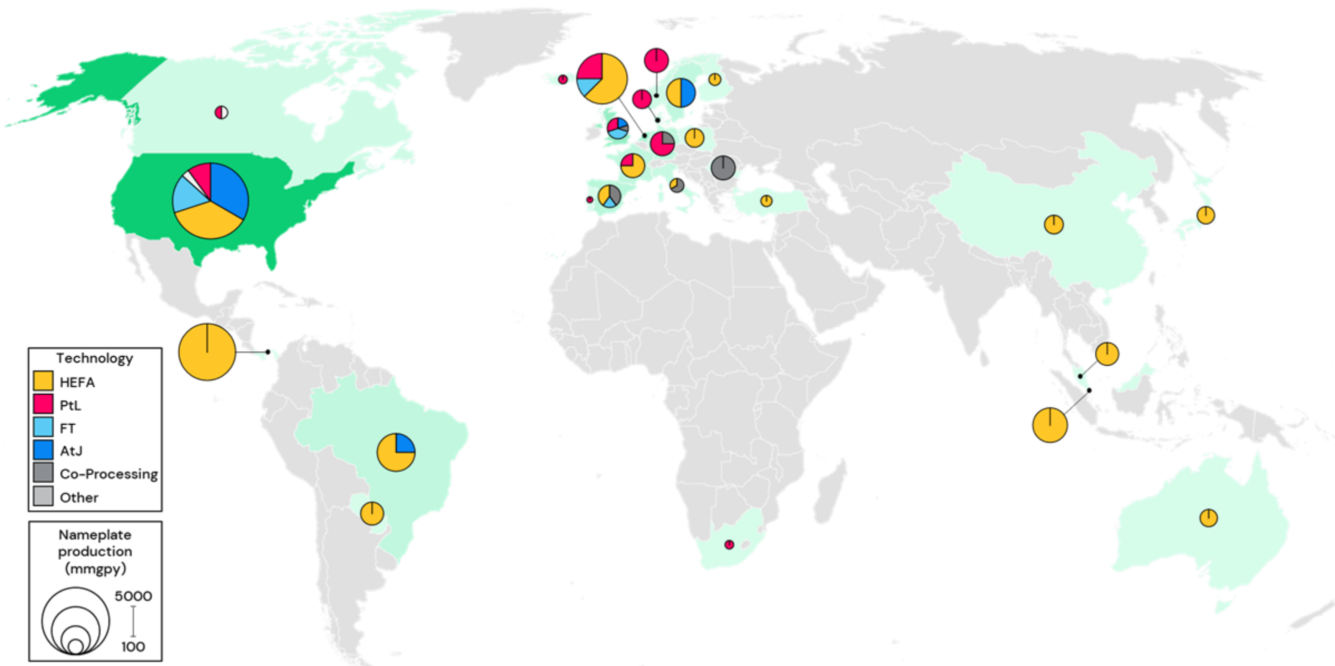
Meeting the demand created by these policies is creating an active international trade in feedstocks and fuels. The HEFA pathway for SAF and renewable diesel production requires used cooking oil and tallows, and the EU

[130] https://www.eia.gov/international/analysis/country/JPN

currently relies on 54% of imported UCO to supply their renewable fuel production facilities[131] – some of which are sourced from Japan. The capacity growth in the EU and the US will create a global pull for waste oil and fat feedstocks. Japan may be able to attract local supply, although this would require competing with the established policies and markets in other countries.

Majority of HEFA feedstocks are expected to flow into Asian and European countries with several European countries shifting to PtL by the end of this decade

Global SAF production by technology pathway, location, and volume (mmgpy) announced by 2030



Source: ICF tracking of public announcements of SAF market developments

As the number of announced SAF facilities increases, it becomes increasingly important for Japan to manage and control the export volumes flowing from the country to other nations. By doing so, Japan can secure a reliable supply of key feedstocks and maintain economic value, ultimately contributing to its economic stability and self-sufficiency.

3. Assessment of SAF feedstock and fuel import opportunities

ICF considered three opportunities for imports within the Japanese SAF market:

- **Used Cooking Oil and tallows,** for production via the HEFA pathway
- **Ethanol**, from sugarcane, corn or cellulosic material for conversion using the AtJ pathway
- **Hydrogen** for use in the PtL pathway

[131] https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/oil/040122-saf-demand-on-the-rise-but-feedstock-availability-a-concern-industry-experts

While UCO is currently in high demand, it is anticipated that as the SAF market matures and production technologies advance, other feedstocks such as ethanol used for Alcohol-to-Jet (AtJ) and hydrogen used for PtL SAF production will gain prominence. As the SAF market continues to grow, diversifying the feedstock base becomes crucial to ensure a sustainable and robust supply chain.

Moreover, the opportunity for imports can be assessed from two perspectives: importing feedstocks to produce fuel domestically, or importing neat SAF. Importing feedstocks can aid in diversifying energy sources, creating additional employment, and supporting the continued use of existing crude oil infrastructure. With refineries expected to either close or operate at reduced capacities, transitioning to renewable feedstocks would contribute to maintaining economic value and employment within the sector.

To date, ITOCHU is the sole importer of SAF in Japan and is supporting the development of an SAF supply chain to facilitate blending. On March 30th, 2023, ITOCHU announced their first delivery of SAF to Central Japan International Airport from Neste OYJ in cooperation with Fuji Oil Company[132]. This SAF is subsequently supplied to All Nippon Airways, Japan Airlines, and other domestic and foreign commercial airlines. No other announcements have been made regarding the import of neat SAF.

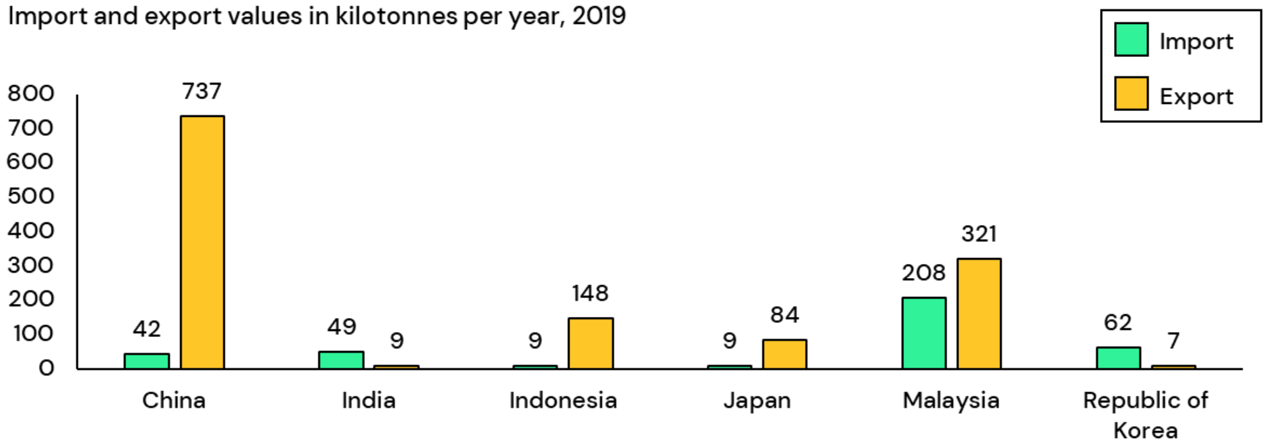
As the SAF market evolves, there is potential for various feedstocks to play a more significant role in its development. Additionally, importing resources can be a strategic move to meet the Japanese SAF target, create jobs, and sustain economic value, particularly in the context of changing refinery dynamics and the shift towards renewable alternatives.

Used Cooking Oil (UCO)

UCO is extensively used to meet existing biofuel mandates in both Europe and the United States, with the demand for biofuel within Asia (including Japan) increasing as well. UCO is extensively traded in and outside of Asia. Besides exports to the EU and US, China and Indonesia export UCO to Malaysia and Indonesia. China and Japan export to the Republic of South Korea. Meanwhile, Japan also imports UCO from Malaysia and China. This intra-Asia trade is reflective of the existing demand that is impacting incentives for both UCO collection and exports for the increased demand for biofuels, including SAF.

[132] https://www.itochu.co.jp/en/news/press/2023/230330.html

Asia exports significant amount of UCO, with majority exported from China and Malaysia



Source: ICCT study utilizing UN Comtrade values

To date, Japan exports more UCO than it utilises domestically. The biodiesel and SAF market in Japan is limited, currently with no financial incentives from the government and no national biodiesel program. Nonetheless, several municipalities have programs that focus on biodiesel production from UCO. Approximately 15 million litres of UCO biodiesel were consumed in Japan in 2021, and 9 million litres were exported[133]. Japan is working to expand the use of UCO as a feedstock for biodiesel to the production of SAF. For example, domestic SAF projects have recently been announced, including the joint venture between JGC, Revo International, and Saffaire Sky Energy, requiring an estimated 900,000 litres of UCO per year[134].

It is important to note recent project announcements in neighbouring countries, including China's Sinopec HEFA facility[135], limiting the amount of UCO exported from China due to domestic use requirements. Although there is competing use for UCO in Asia, there is an opportunity for excess or unutilised volumes to be exported to Japan. Japan offers favourable economics of lower insurance and freight costs associated with shipping compared to alternative destinations like Europe and the United States.

Ethanol

Under the Ethanol Business Act[136], METI monitors the production, importation, and sales of ethanol exceeding 90 per cent alcohol content by volume. Japan utilises ethanol exceeding this 90% for the production of biofuels (ethyl tert-butyl ether, ETBE). Currently, over 90% of ETBE consumed in Japan is imported. The remainder is produced locally from imported Brazilian sugarcane-based ethanol.

In 2009, to encourage the replacement of fossil fuels with renewable energy sources, Japan introduced the Act on Promotion of Use of Non-Fossil Energy Sources and Effective Use of Fossil Energy Raw Materials by Energy

[133] https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Biofuels%20Annual_Tokyo_Japan_JA2022-0109.pdf
[134] https://www.argusmedia.com/en/news/2436927-japanese-firms-to-secure-domestic-uco-for-saf-output
[135] https://aviationweek.com/air-transport/aircraft-propulsion/china-producing-first-industry-scale-saf-supply
[136] Microsoft Word - h12Aa000360101en9.0_h17A32.doc (fao.org)

Suppliers[137] (Sophisticated Methods of Energy Supply Structure Act). This directed METI to develop basic policies and guidelines, and in 2010, they published their first biofuel standard, laying the groundwork for Japan's decision to use bioethanol to fulfil its biofuel commitment for on-road transportation. This standard outlined an annual biofuel target volume of 210 million litres of crude oil equivalent (LOE), which later increased to 500 million litres of LOE (approximately 823.7 million litres of bioethanol). It also outlined a default GHG emission value for Brazilian sugarcane-based ethanol. METI published updated guidelines in 2020, including the default GHG emission values for US corn-based ethanol. GHG emission values for both Brazilian and US imported ethanol were updated in the recently proposed biofuel standard to be in place from 2023 to 2027. Under this standard, the 500 million LOE requirement remains consistent, however, it will now recognize the use of SAF in addition to bioethanol to meet this requirement. For SAF manufactured from certain feedstocks[138], METI will allow the derived SAF volume to count twice toward the 500 million LOE target. This introduction is likely to increase the use and requirement of SAF, driving additional import volumes.

To date, Japan depends heavily on ethanol imports which have steadily grown since 2001, with the majority of the imports coming from Brazil and the United States. For example, Japan imported approximately 854 million litres of ethanol in 2020, with approximately 80% coming from Brazil, 13% from the United States, and the rest from other countries.

To date, Japan does not produce SAF on a commercial scale, however, Idemitsu Kosan company received 29.2 billion yen for a 5-year project to develop and commercialize its SAF supply chain using AtJ. The project will require 190 million litres of bioethanol per year to produce 100 million litres of SAF. By 2030, Idemistsu aims to launch a second SAF plant with the expected capacity of both facilities to reach 500 million litres of SAF per year[139].

The following sections outline policy developments and imports from the US and Brazil to Japan.

United States (US)

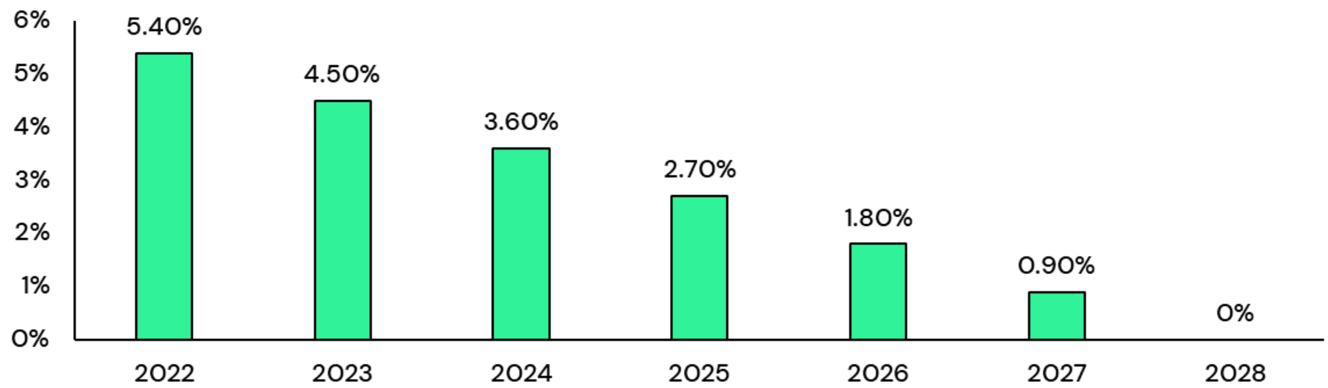
In 2022, the US and Japan issued a Joint Leaders Statement[140] outlining the commitment to take all available measures to increase the demand for bioethanol by 2030, including for SAF and on-road fuel, to reduce Japan's dependence on imported crude oil. Japan's recent draft biofuel standard would allow the US to capture up to 100% of Japan's on-road ethanol market. Exports from the US are expected to increase to 80 million gallons annually, representing an additional USD 150-200 million in exports[141].

[137] JEMA -Policies Concerning New Energy- (jema-net.or.jp)
[138] Cellulosic raw materials (e.g. trees), cellulosic raw materials in collected used products, carbon recycling technology, microalgae, used cooking oil, animal fats and other non-edible oils.
[139] Our world's first 100,000 KL class ATJ commercial plant project have been adopted by NEDO Green Innovation Fund. - Contributing to energy transitions in the aviation industry - | News releases | Idemitsu Kosan Global
[140] https://www.whitehouse.gov/briefing-room/statements-releases/2022/05/23/japan-u-s-joint-leaders-statement-strengthening-the-free-and-open-international-order/#:~:text=Toward%20Building%20a%20Future%2DOriented,prosperity%2C%20and%20freedom%20are%20ensured.
[141] Japan's New Biofuels Policy Allows for Increased Exports of U.S. Ethanol | United States Trade Representative (ustr.gov)

Additionally, under the 2020 US-Japan Trade Agreement (USJTA), Japan committed to providing substantial market access for the US by phasing out most tariffs. This will eliminate the 10 per cent tariff on ethanol imports, including fuel ethanol used for direct blending.

Under the US Japan Trade Agreement, Japan will eliminate the 10% tariff on ethanol used for direct blending

Tariff Reduction Staging Table under USJTA (HS: 2207.10-199)



Source: USDA Japan Biofuels Annual Report

Brazil

In 2016, Brazil launched the RenovaBio program to support the country's commitments under the Paris Agreement and to promote the production, commercialization, and use of biofuels. Under this program, total Brazilian ethanol production reached an estimated 32 billion litres in 2022, exporting a total of 1.55 billion litres. Brazil exports the majority of ethanol volumes to South Korea and the US due to a favourable Carbon Intensity (CI) rating that Brazilian sugarcane ethanol receives under the California Low Carbon Fuel Standard (LCFS). Additionally, Brazilian ethanol is also frequently shipped to the Gulf Coast to be converted to ETBE for further shipment to Japan. Total export volumes to Japan reached 77 kiloliters in 2021, valued at USD 46 million FOB[142].

Hydrogen

The government of Japan recently adopted a revision of its Basic Hydrogen Strategy[143], centred on increasing the use of hydrogen as a fuel, with plans to invest more than $100 billion in hydrogen supplied over the next 15 years. This strategy is aligned with Japan's Green Growth Strategy, adopted in 2021, which aims to increase the volume of hydrogen to up to 3 million tonnes in 2030, and 20 million tonnes in 2050[144]. The Basic Hydrogen Strategy specifically outlines the production of synthetic fuel (e-fuel) to be utilised for the decarbonisation of the aviation industry. In this context, the strategy sets a goal of achieving commercialization of e-fuels in the

[142] Free on Board (FOB) is defined as the value of exports is the value of goods at the time of export
[143] 20230606_5.pdf (meti.go.jp)
[144] Japan's Green Growth Strategy Will Accelerate Innovation | The Government of Japan - JapanGov -

first half of 2030, through the development of large-scale and highly efficient manufacturing technology to support domestic and overseas projects.

In December 2020, nine Japanese companies formed the Japan Hydrogen Association (JH2A), which is working to establish a hydrogen supply chain, in partnership with global entities. The nine companies include ENEOS, Iwatani, Kawasaki Heavy Industries, Kobe Steel, Mitsui & Co, Sumitomo Mitsui Financial Group, Kansai Electric Power, Toshiba, and Toyota.

Additionally, GOJ has expressed interest in working with other countries to collaborate on cutting-edge technology innovation and to establish global value chains. Over the past year, several announcements have been made outlining strategic agreements between Japan the United Arab Emirates (UAE) and Australia, to cooperate on hydrogen and other clean energy transition technologies. The following sections outline the development of Hydrogen in both the Middle East and Australia, as well as its imports into Japan.

United Arab Emirates

In 2021, Japan and the UAE signed a memorandum of cooperation (MoC) on hydrogen to exchange hydrogen policy and standard development and to build an international supply chain including the production and transportation to Japan. This is based on a joint effort to enhance industrial cooperation and to drive new opportunities in hydrogen and renewables. Later that year, the UAE published their Hydrogen Leadership Roadmap[145], which outlined a target of 25% market share of low-carbon hydrogen and derivatives and key import markets by 2030, with a focus on Japan.

The collaboration between Japan and the UAE, sparked several announcements, including a joint study agreement between Abu Dhabi National Oil Company (ADNOC), INPEX Corporation, JERA, and the Japan Oil, Gas, and Metals National Corporation (JOGMEC) to explore the commercial potential of blue ammonia production in the UAE. More recently, Japan's Mitsui, along with South Korea's GS Energy, agreed to take stakes in a blue ammonia plant being developed at Ruwais, UAE, joining with ENEOS and ADNOC to evaluate the development of a commercial clean hydrogen supply chain between the UAE and Japan. This project will conduct technical and engineering certification of a hydrogen production facility with a capacity of 50,000 Mt/year and a feasibility study on the potential to expand this facility to commercial production of 200,000 Mt/year[146]. Following this collaboration, METI and ADNOC announced the establishment of the Japan-UAE Collaboration Scheme for Advanced Technology, which includes collaboration on decarbonisation technologies.

Australia

In 2018, a consortium of companies, including Kawasaki Heavy Industries, J-Power, Iwatani Corporation, Marubeni Corporation, Sumitomo Corporation, and AGL Energy, announced the Hydrogen Energy Supply Chain (HESC) pilot project, which received AUD 500 million in funding contributions from the Australian government and 220 billion yen from the Japanese Green Innovation Fund. This pilot project consisted of a hydrogen

[145] UAE Hydrogen Roadmap -Eng.pdf
[146] Japan's ENEOS, Mitsui agree to study 200,000 Mt/year hydrogen supply chain with UAE's ADNOC | S&P Global Commodity Insights (spglobal.com)

production plant, located in Latrobe Valley, to produce hydrogen using brown coals and biomass, as well as the development of the world's first hydrogen tanker the Suiso Frontier.

From the success of this pilot project, Japan and Australia agreed to cooperate in facilitating the carbon-neutral goals of the Paris Agreement by announcing the Japan-Australia Partnership on Decarbonisation through Technology[147], followed by the Australia-Japan Clean Hydrogen Trade Partnership[148]. Following this, the HESC project celebrated the successful voyage of the Suiso Frontier from Australia to Japan and is discussing a commercialization phase which is expected to produce an estimated 225 kilotonnes of carbon-neutral liquefied hydrogen[149].

In 2023, ENEOS Corporation also announced the construction of a demonstration plant in Brisbane, Australia, to produce methylcyclohexane (MCH), a hydrogen carrier, using their low-cost Direct MCH method. The demonstration plant will produce green MCH using a 250-kilowatt solar system in Queensland, which is ideal for solar generation. During the demonstration period, MCH equivalent to 2 to 3 tons of hydrogen will be produced and transported to Japan, where hydrogen will be extracted from the MCH in ENEO's Central Technical Research Laboratory. ENEOS is further working to develop production technology for stable and cost-competitive green hydrogen[150] in Australia[151].

Australia's National Hydrogen Strategy[152] which outlines more than AUD 1.3 billion in investments in the development of its hydrogen industry, includes an AUD 150 million Australia Clean Hydrogen Trade Program to support Australian-based hydrogen supply chain projects and secure overseas public or private sector investment, with a focus on the export of clean hydrogen to Japan.
According to the International Agency's 2022 World Energy Outlook, Australia is expected to become the second-largest net exporter of low-emission hydrogen by 2030 and the largest by 2050. Due to ample low-cost solar and wind energy, Australia's hydrogen production from renewable electricity could reach 3 million tonnes of hydrogen by 2030, based on announced hydrogen projects and partnerships[153].

Summary of hydrogen import opportunities

Japan has led the world in hydrogen partnerships, with a sophisticated network of agreements to produce and import hydrogen. Supported by the demand created by the Japan hydrogen roadmap, imported support is expected to rapidly increase, particularly for applications allowing direct use, such as chemicals, fuel cells and combustion. However, for PtL SAF production, economics may favour the conversion of the hydrogen into SAF before importation. Hydrogen is relatively challenging to transport long distances, with a low volumetric energy density requiring large spaces, and complex infrastructure required to compress or liquefy the hydrogen, in addition to the energy losses. By comparison, liquid SAF can be imported at ambient temperatures, and has a

[147] Japan-Australia partnership on decarbonisation through technology | Ministers for the Department of Industry, Science and Resources
[148] Australia Japan Clean Hydrogen Trade Partnership | Ministers for the Department of Industry, Science and Resources
[149] Home - HESC (hydrogenenergysupplychain.com)
[150] Green hydrogen is defined as hydrogen produced using renewable electricity instead of fossil fuels, resulting in lower greenhouse gas emissions during production.
[151] 20230130_01.pdf (eneos.co.jp)
[152] State of Hydrogen 2022 - DCCEEW
[153] Australia 2023 Energy Policy Review (windows.net)

significantly higher volumetric energy density, with both factors greatly reducing the transport costs. As a result, most hydrogen for SAF may likely be processed in other countries and imported as liquid fuel. However, there may be a residual opportunity for imported hydrogen to smooth any volatility in domestic production for PtL, and to ensure the SAF refining infrastructure is built, with Japan possessing much greater control over domestic facilities.

4. Discussion

The international market presents significant opportunities for Japan to import feedstocks, intermediaries, and neat SAF. Considerable Used Cooking Oil (UCO) is already traded internationally, and Japan may be able to access some of this supply as domestic comes online. Ethanol imports into Japan have been steadily rising but still represent a fraction of the global market. Nearly 30 billion gallons[154] of ethanol are produced globally, and as road vehicle efficiencies improve and electric vehicles proliferate, much of this ethanol may need to flow to alternative markets. The combination of surplus ethanol supply and aviation demand could create a significant opportunity for Japan to use imported ethanol to meet SAF targets.

Hydrogen is emerging as a crucial component of Japan's green energy strategy, with significant investments planned for both domestic production and imports. Collaborations with countries like the United Arab Emirates and Australia are expected to secure a stable supply of hydrogen, which can also be used for SAF production, although much of this may be refined locally into liquid SAF for ease of transport.
While the current SAF market is relatively small, it is expected to rapidly grow over the next decade. This capacity growth may create some opportunities to import SAF, although current production projections fall short of demand, suggesting continued scarcity. Clear demand from Japan and other countries may be necessary to catalyze the production growth required for imports.

To achieve its target of replacing 10% of jet fuel consumption with SAF by 2030, Japan faces both challenges and opportunities to access imports. The potential volumes are significantly greater than Japan's demand, but the markets may be increasingly competitive. Imports would likely be diversifying energy sources and may reduce costs but would catalyze less economic growth and domestic investment compared to imports. The balance is likely to be driven by government priorities and priorities.

Export opportunity

According to Santander Trade, Japan ranked as the fifth largest exporter of goods in 2023, accounting for 37% of the country's GDP[155]. In 2023 (fiscal year), Japan's exports were predominantly transporting equipment, machinery, motor vehicles, and electrical machinery, providing an estimated revenue of 40 trillion yen[156]. Japan's export success is fueled by a rich history of technological advancements, research and development, and a skilled workforce. The strategic global positioning of Japanese corporations has enabled them to adapt to evolving market demands and remain competitive on the international stage. As Japan continues to explore

[154] Annual Ethanol Production (ethanolrfa.org)
[155] https://santandertrade.com/en/portal/analyse-markets/japan/foreign-trade-in-figures#:~:text=Japan%20is%20the%20world's%205th,(World%20Bank%2C%202023).
[156] https://www.customs.go.jp/toukei/shinbun/trade-st_e/2023/202335ee.xml#pg3

new markets and invest in emerging technologies, its export industry remains pivotal to the country's economic resilience and global influence.

While domestic feedstocks provide limited opportunity for export due to their higher economic value within domestic markets, Japan can capitalize on its extensive technological expertise to pioneer and globally commercialize advanced SAF technologies. LanzaJet, a prominent sustainable fuels technology company, initially developed its groundbreaking technology in the United States. Presently, their innovative solutions are being implemented in various countries, including the EU, the UK, India, Australia, and New Zealand.

Although there is limited opportunity for SAF feedstocks to be exported due to providing higher economic value domestically, there is an opportunity for Japan to leverage years of technological expertise and knowledge to develop and commercialize advanced SAF technologies to be exported and utilised in other countries. LanzaJet, a leading sustainable fuels technology company and producer, first developed its technology in the United States. Today, however, their technology is being used in the EU, the UK, India, Australia, and New Zealand.[157]

The ATAG Waypoint 2050 study projects a financial requirement ranging from 1,080 to 1,450 billion US dollars for the development of essential infrastructure to build sufficient SAF capacity. Furthermore, the study outlines the necessary investments in the Asia Pacific region, estimated to fall within the range of 421 to 554 billion US dollars. The study further states that the level of investment will become increasingly achievable as additional producers enter the market, fossil infrastructure is increasingly available for retrofitting and investors look to decarbonise portfolios. As an example of this, there has been a notable trend of financial institutions and consortium groups gathering investment funds to support the SAF industry. An example of this is the United Airlines Ventures Sustainable Flight Fund[158], which has reached $200 million in investments from consortium partners, such as American Express Global Business Travel, Aramco Ventures, Aviation Capital Group, Bank of America, Boeing, and others.

Sustaining growth in the SAF industry demands continued investments aimed at mitigating risks associated with production technologies. Leveraging its global reputation for excellence in producing high-quality goods and pioneering technologies, Japan stands at the forefront of this transformative endeavour. The study underscores that a significant portion of Japan's available feedstocks are comprised of advanced resources like woody biomass and Municipal Solid Waste (MSW). However, the utilisation of these feedstocks requires technologies that are not yet proven commercially viable.

This presents a unique opportunity for Japan to utilise its domestic knowledge and expertise. By doing so, the country can play a pivotal role in supporting the development of a robust domestic SAF infrastructure while simultaneously contributing to the global SAF industry. Key to this effort is the development and de-risking of advanced technologies, such as Power-To-Liquids. Successful development and de-risking offer a significant opportunity for Japan to export these technologies to the global market.

[157] https://www.lanzajet.com/where-we-operate/
[158] https://www.united.com/en/us/fly/company/responsibility/united-airlines-ventures.html

Photo by Eva Bronz

Section 3: SAF production and technology

1 Introduction to SAF technology pathways

ASTM approved pathways

SAF can be made using a range of conversion pathways and feedstocks. Once produced, SAF is operationally identical to kerosene and can be used with existing infrastructure and aircraft up to a 50% blend. Today, only seven technology pathways (and two co-processing pathways) for SAF production are approved by the American Society for Testing and Materials or ASTM, the recognised body to approve the suitability of jet fuel for aircraft. Only the HEFA pathway (which produces fuel from feedstocks such as waste vegetable oils) is commercially mature, although considerable effort is ongoing to scale other pathways, particularly Alcohol-to-Jet (AtJ), and Fischer-Tropsch (FT). Other production pathways, such as HTL and methanol-to-jet, are proceeding through the approval process by ASTM, and it is expected that the pathways available for SAF production will increase over time.

Table 1: ASTM-approved pathways for SAF production

Pathway	Feedstock	Max. Blending Limit
FT-SPK	Biomass (e.g. trash/rubbish, forestry residues, grasses)	50%
HEFA-SPK	Waste lipids & fats (e.g. UCO, tallow, DCO)	50%
HFS-SIP	Sugars to hydrocarbon (e.g. molasses, sugar beet, corn dextrose)	50%
FT-SPK / A	Same feedstock as FT-SPK, but slightly different process	10%
ATJ-SPK	Agricultural waste (e.g. forestry slash, crop straws)	50%
CH-HK	Plant and animal fats, oils and greases (FOGs)	50%
HC-HEFA-SPK	Bio-derived hydrocarbons, fatty acid esters	10%
Co-processed HEFA*	Fats, oils, and greases (FOG) co-processed with petroleum	5%
Co-processed FT	Fischer-Tropsch hydrocarbons co-processed with petroleum	5%

* Approved under ASTM D1655 Annex A1
Source: https://www.icao.int/environmental-protection/GFAAF/Pages/Conversion-processes.aspx

Feedstock mapping

The appeal of each feedstock is predominantly influenced by its environmental qualities, conversion feasibility, and cost, while limitations in environmental sustainability and competition for resources will place constraints on the aviation industry's long-term utilisation potential. Opting for a specific feedstock plays a pivotal role in shaping the necessary infrastructure and can account for up to 85% of the overall cost of fuel production.

Consequently, a comprehensive understanding of various feedstocks is important when evaluating the trajectory of the development of the SAF industry.

The environmental attributes, ease of conversion and cost will drive the relative appeal of each feedstock, while environmental limitations and competing demands will constrain the volume that the aviation industry can reasonably expect to use over the long term. The choice of feedstock determines the infrastructure required and can drive up to 85% of the cost of the fuels produced, so understanding the feedstocks is critical to assessing the development of the SAF industry.

The variety of potential feedstocks is illustrated by the Commercial Aviation Alternative Fuels Institute (CAAFI), which lists over 130 distinct categories. Only some of these apply to Japan, and the opportunities have been grouped into five categories, as illustrated below.

Table 2: Feedstock opportunities for Japan

Feedstock category	Sub-category	Example feedstocks	Conversion pathways
Biological feedstocks			
Waste and residue lipids	N/A	UCO and Tallow	HEFA
Agricultural residues	N/A	Corn stover, rice residues, bagasse	Gas/FT or AtJ
Woody biomass	N/A	Forestry coppice, slash, thinnings, offcuts	
Municipal solid waste	N/A	Black bin and industrial solid waste	
Non-biological feedstocks			
Renewable fuels of non-biogenic origin (RFNBO)	Industrial waste gases	Waste carbon gases from industrial plants	Gas/FT or AtJ
	PtL (H2 from electrolysis and CO2 from DAC)	Renewable electricity	

Technology readiness

The different SAF pathways are at different levels of commercial maturity, as measured by their technology readiness levels (TRL). This system ranges from Stage 1 to Stage 9, as outlined in the Appendix.

Apart from HEFA, SAF production is mostly at low to mid-TRL, with few large-scale projects operating. Analysis shows that HEFA currently has the highest TRL (reaching TRL 9), with FT on the cusp of commercialization (stage 8), as facilities such as the Fulcrum Sierra plant undergo commercial deployment. AtJ is currently at stage 7, although the commissioning of the LanzaJet Freedom Pines plant and the Gevo NZ-1 will see this pathway achieve full commercialization. HTL is at TRL 5, yet to be approved by the ASTM.

As the most mature technology, the HEFA pathway is the most widely used today to convert fats, oils and greases (FOGs) into jet fuel and renewable diesel. This conversion process requires relatively little capital investment and requires producers to take on limited technical risk. However, the feedstock availability is constrained, and the price of FOG is volatile, limiting the potential to scale this pathway.

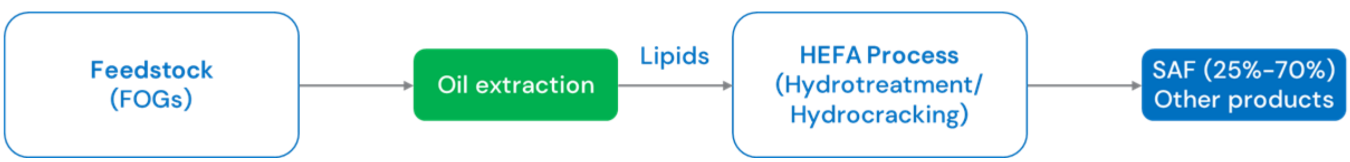
The AtJ and FT pathways are currently undergoing commercial deployment. These pathways can be used for processing advanced generation feedstocks, such as municipal solid waste (MSW), woody biomass, agricultural residues, industry waste gases, and direct air capture carbon dioxide into sustainable aviation fuel. The AtJ pathway requires alcohol as the intermediate input (isobutanol or ethanol), made by direct fermentation of feedstocks or through fermentation of carbon monoxide by engineered microbes. The FT pathway uses syngas (a mixture of hydrogen and carbon monoxide) as a feedstock. The syngas can be produced by gasification of solid feedstocks, or through the Power-to-liquid approach, which combines a sustainable source of carbon with green hydrogen.

2 SAF technology pathways

HEFA

HEFA feedstocks are waste and residue lipids, such as used cooking oil and waste animal fat, as well as sustainably grown oil crops. Depending on the feedstock, HEFA provides a GHG emission savings potential of 50%-85%, which can be slightly increased through the use of low-carbon hydrogen in the hydroprocessing step of the production process and carbon capture integration. It has a conversion ratio of c. 0.9 mass of inputs to mass of fuel produced, of which SAF ranges from 0%-70%, depending on the needs of producers and plant economics.

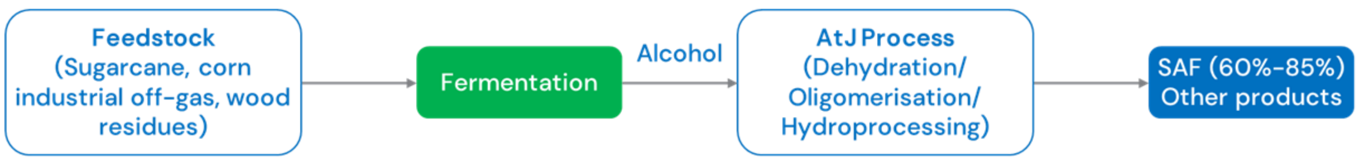
HEFA process (simplified)



Alcohol-to-Jet (AtJ)

The AtJ pathway can use any biomass that can be fermented into ethanol, including corn, sugarcane, and cellulosic materials such as forestry wastes, and agricultural residues. Industrial waste gas can also be used as a feedstock, through the utilisation of engineered microbes to convert the waste gases into ethanol. This pathway offers an emissions reduction potential of about 20%- 95%, with the range strongly dependent on the feedstock, particularly the direct/indirect land-use impact. The conversion rate for the AtJ pathway is estimated at around 45%, with SAF consisting of up to 78% of the product.

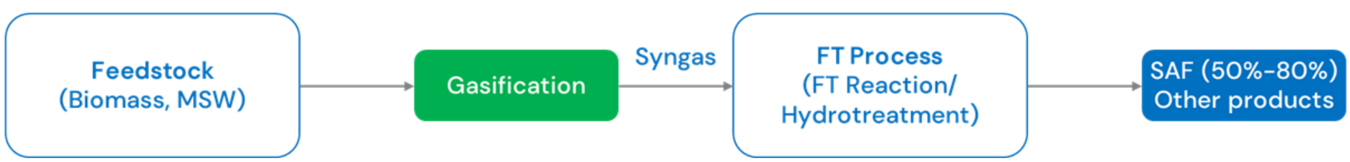
AtJ process (simplified)



Fisher Tropsch (FT)

The FT pathway can use any feedstock which can be gasified to produce syngas – a mixture of carbon monoxide (CO) and hydrogen – which is subsequently fed into a Fischer-Tropsch reactor where it is combined into a mix of hydrocarbons in the presence of a catalyst. The process consists of the following key steps: feedstock pretreatment (sorting, sizing and drying), gasification, syngas clean-up and conditioning, FT catalysis, distillation and hydrocracking. Special attention has to be paid to controlling the H2:CO ratio in the syngas as this has an important effect on the reaction output. The pathway offers CO2 emission reductions of 85%-94%, and potentially well over 100% of significant CO2 is captured and sequestrated during the process. The feedstock conversion rate to total output assumed is 40%, and the jet-optimized SAF yield is 60% on average.

FT process (simplified)

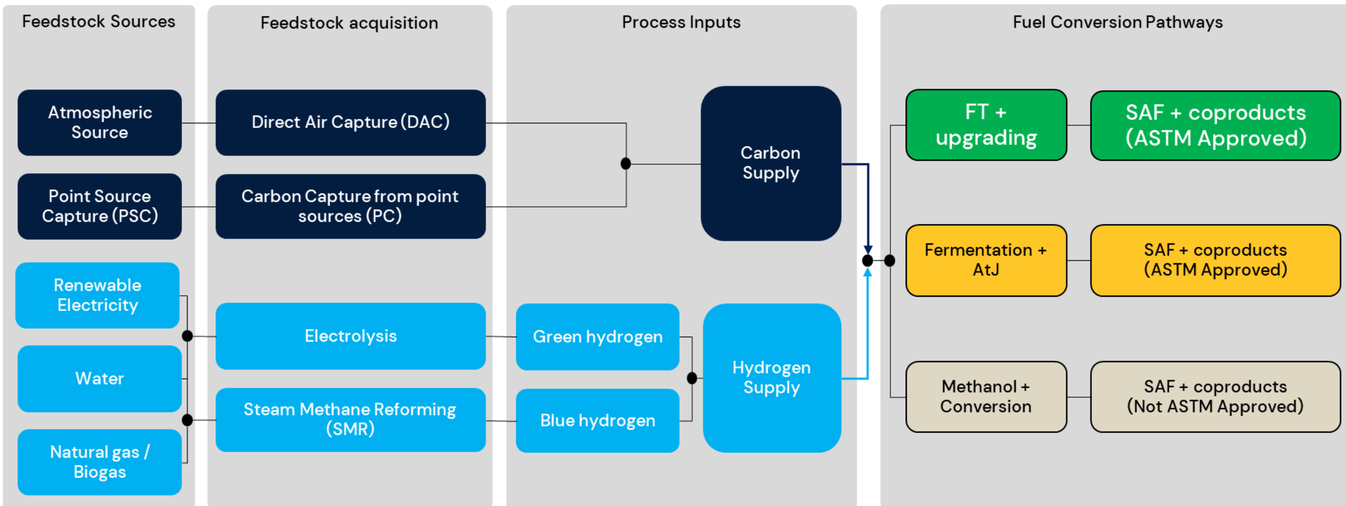


Power-to-Liquids (PtL)

There are various feedstocks and technologies to produce SAF through the PtL approach. Hydrogen can be supplied from SMR+CCS, electrolysis or gasification of biomass for hydrogen, and the CO2 can be sourced from point sources or the atmosphere.

The FT process is the current focus for PtL production, but the methanol-to-jet route is also progressing through development and certification. The FT route converts syngas (CO and H2) into a mix of long-chain hydrocarbons, which is then upgraded into final products, including aviation fuel (SAF). The methanol-to-jet pathway converts syngas into liquid methanol through catalytic reactions, which can then be processed into SAF. In addition to its use for aviation fuel production, synthetic green methanol can also be used in road and marine transportation. PtL has the potential to provide up to 99% emissions reduction, with 65% SAF output on average.

The Power to Liquid SAF production process



HC-HEFA-SPK (production of algae-based biofuel)

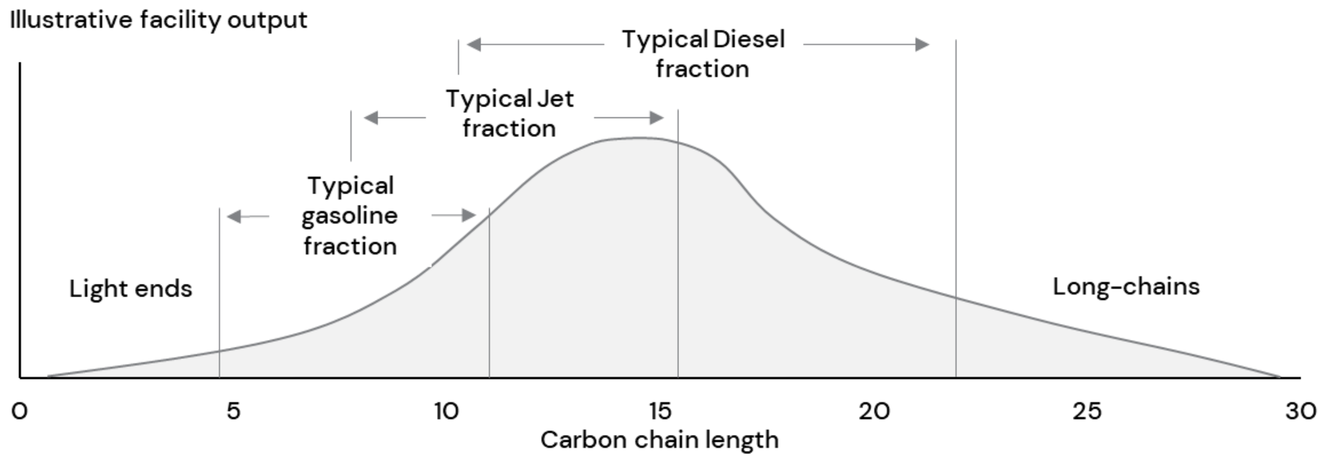
In May 2020, Annex A7 was approved and announced by ASTM, which establishes criteria for the production and use of a type of synthesized paraffinic kerosene from hydrocarbon-hydroprocessed esters and fatty acids (HC-HEFA-SPK). The standard provides that HC-HEFA-SPK fuel, the development of which was led by Japan's IHI Corporation, may be blended at up to 10% by volume with conventional jet fuel.

As a part of the NEDO project, which started in 2017, IHI developed a next-generation technology for the mass-production process of microalgae, Hyper-Growth Botryococcus Braunii (HGBb), and fuel manufacturing process of algal oil produced by the microalgae. Japan Airlines successfully utilised the SAF produced via this method in 2021 to fly from Tokyo to Osaka. In collaboration with Honeywell UOP, IHI has announced plans to build a supply chain for fuel production and supply of algae-based SAF.

3 SAF production

As a hydrocarbon fuel, SAF has similar physical properties to naphtha, gasoline, diesel, and other fuels. For example, diesel has a slightly longer-chain hydrocarbon chain (10-22 carbon) compared to jet fuel (8-16). Consequently, the production processes for RD and SAF are similar, requiring only a small piece of additional infrastructure at the facility.

Every facility will produce a range of carbon chain outputs, different processes can optimise toward specific factions



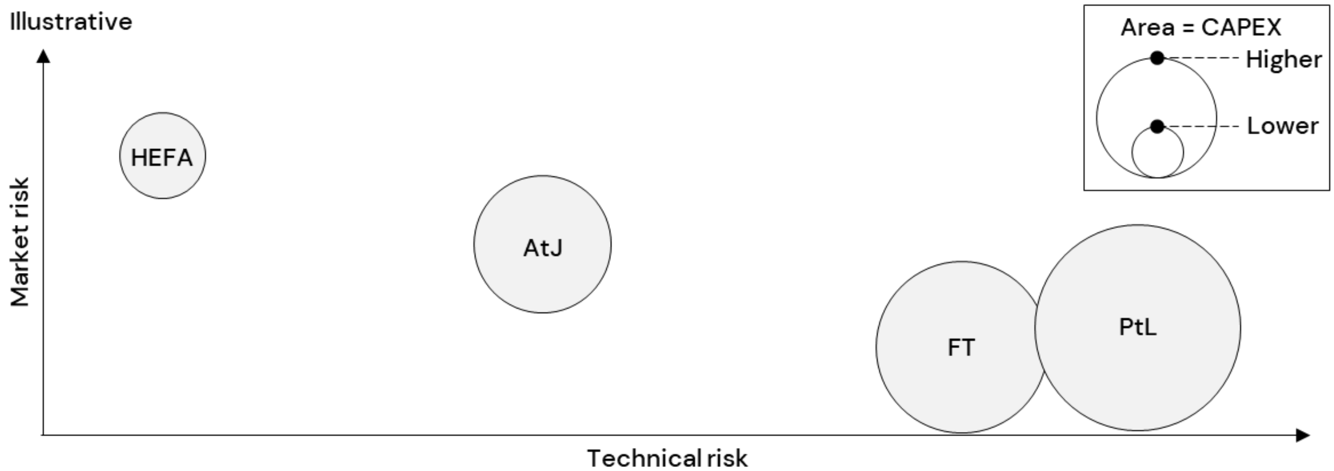
Source: ICF analysis

This similarity to other fuels is both an advantage and a challenge for SAF production. It means that SAF producers can draw on some of the mature technologies that have already been de-risked by the RD industry, facilitating the rapid deployment of capacity. However, economics in countries such as the US currently favour RD production over SAF, meaning that much of the feedstock, capital, and expertise that could be used for SAF is currently utilised for RD production.

4 Technology scaling and future projections

Different SAF production technologies offer different market and technical risks. HEFA is the most mature technology but has significant exposure to the feedstock market. Volatile prices of the HEFA feedstocks and their limited supply increase the market risks for HEFA. On the other end of the spectrum, there is PtL technology with potentially much lower exposure to the feedstock market if the electricity price is fixed through long-term power purchase agreements (PPAs). This spectrum has been illustrated in the following diagram, although each facility will bring bespoke risk profiles.

HEFA has the lowest CAPEX with high exposure to the feedstock market, whereas PtL has high technical risks and low exposure to the feedstock market

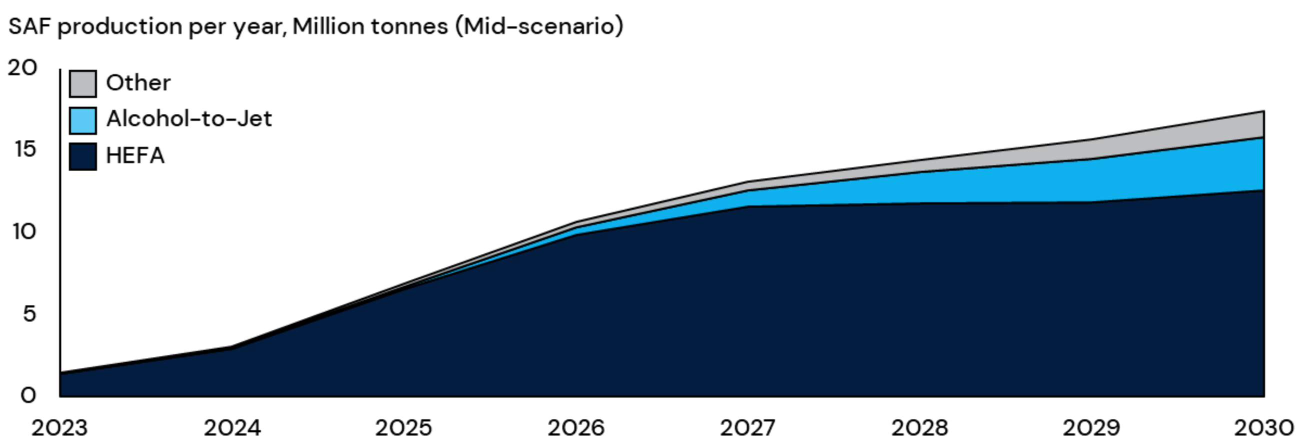


Source: ICF analysis

Increasing policy support is driving an acceleration of the SAF industry, and the HEFA pathway is expected to provide the majority of capacity over the next decade. Several large fossil facilities are undergoing refits to process renewable feedstocks, including the Neste facility in Singapore, the Shell facility in Rotterdam, the Total Facility in Grandpuits, and the Phillips 66 and Marathon facilities on the West Coast of the US. Many others add to this capacity and greatly increase the availability of SAF in the coming years.

Only a small number of AtJ and other technologies will come to maturity before 2030, but these will be crucial to demonstrate the potential to process a more diverse range of feedstocks. Notable facilities include the Fulcrum FT plant in Sierra, the LanzaJet AtJ facility in Freedom Pines, the Gevo AtJ NZ-1 facility and the Velocys FT facilities in Bayou and Immingham. A small number of PtL facilities will enter operations before 2030, although these generally offer very small capacities.

HEFA technology is expected to drive SAF supply through 2030

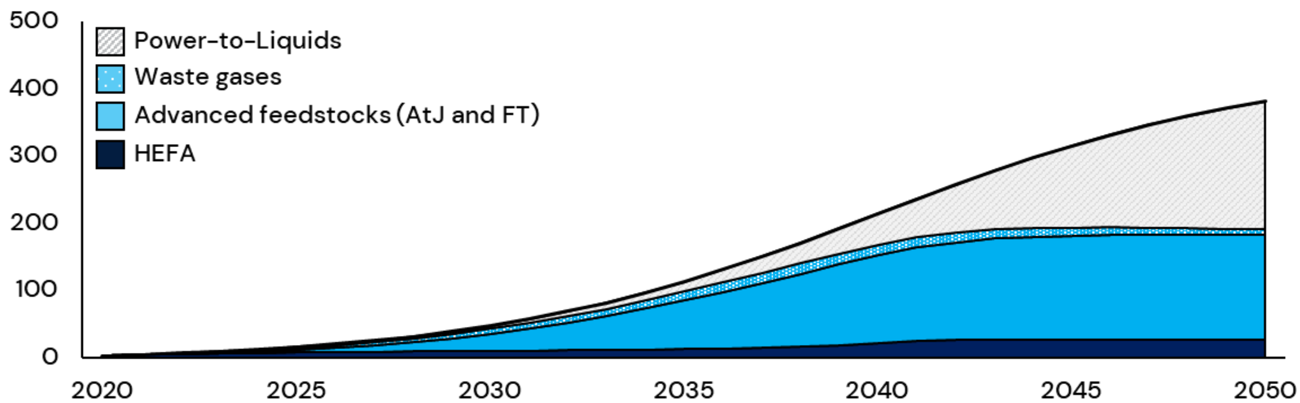


Source: ICF Analysis

Beyond 2030, constraints on the availability of UCO and tallows are expected to result in a plateau in HEFA production, with AtJ, FT, and other advanced technologies accelerating to provide greater supply in the mid-term. The power-to-liquid approach will be increasingly important in the long term, as other feedstocks are increasingly demanded, and the economics of renewable and hydrogen production continue to improve.

HEFA supply is expected to plateau due to feedstock limitations, while PtL supply is expected to substantially increase by 2050

SAF production per year, Million tonnes



Source: ATAG Waypoint 2050 report

Photo by William Justen

Section 4: Policy framework considerations

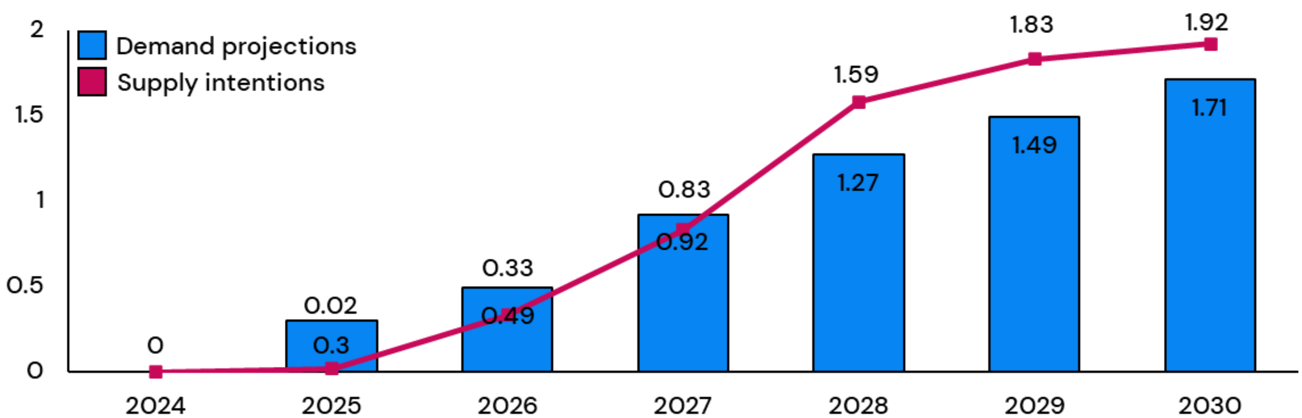
1 Introduction

The cost of production for all SAF technologies is at least several times the cost of production for fossil fuels, due to the differences in (1) scale, with SAF at the early stages of commercialisation, and (2) technical difficulty, with many SAF technologies requiring complex processes to convert sustainable feedstocks such as waste oils, agricultural residues, and municipal waste, into liquid hydrocarbons. The aviation industry serves cost-sensitive customers and cannot absorb or pass through significant incremental costs for SAF without regulation. The importance of aviation to the global economy and connectivity makes it essential that governments recognise and address the challenges.

Increased use of SAF is a key component of the government of Japan's (GOJ) plan to reduce greenhouse gas emissions from aviation. Japan's Ministry of Economy, Trade and Industry (METI) recently announced a planned target volume for SAF under the Sophisticated Act by 2030. This target volume is in alignment with the announcement of the Basic Policy for Promoting Decarbonisation of Aviation by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT). MLIT estimates that if SAF replaces 10% of jet fuel by 2030, SAF demand will reach 1.7 billion litres a year, equivalent to 452 million gallons.

METI announced SAF will account for 10% of jet fuel consumption by 2030, with the forecasted supply volume expected to exceed the announced target

METI forecasted SAF demand and supply, METI, Million kL



Source: METI

The focus on sustainability and scale requires new feedstocks and technologies to convert them. Globally, just under 20% of major crop production (sugarcane, corn, vegetable oils) is used for renewable fuel production, with almost all used on-road. Land constraints, the impact on biodiversity, and carbon limit the ability of these feedstocks to expand. More sustainable and scalable feedstocks exist, such as cellulosic materials, municipal wastes, and renewable electricity. However, the technologies to convert these feedstocks into fuels are at an early stage of development. Commercializing them will be expensive, risky, and essential. Policy to incentivize the research, development, and deployment of these advanced technologies, which will be crucial to support the SAF landscape's transition toward sustainability and scale. Policy can further support the development by driving the supply and demand market of SAF.

The development of a sustained global SAF production industry requires a nuanced approach, recognizing that the opportunities and challenges for SAF production can vary significantly from one state or region to another. Diverse factors such as climate, agricultural systems, available resources, and economic conditions will influence the feasibility of SAF production in each specific area. Additionally, political barriers, existing regulatory frameworks, and economic considerations will differ, making it clear that there is no one-size-fits-all approach to successful SAF policy implementation. Instead, a tailored and customized strategy that considers the unique circumstances and needs of each state or region is likely to be the most effective way to promote and support the growth of the SAF industry on a global scale.

2 Policy context

Global targets and market-based measures

Efforts to reduce carbon emissions in the aviation industry, both on a global and national scale, have been pioneered by the International Civil Aviation Organization (ICAO) and its Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). These initiatives aim to align with the objectives of the Paris Agreement, emphasizing the aviation sector's commitment to addressing climate change and reducing its carbon footprint.

- **Paris Agreement:** Under the Paris Agreement, member states committed to limiting the global average temperature increase to well below 2°C above pre-industrial levels, with an aspiration to limit it to 1.5°C. To achieve this, member states are expected to enhance their Nationally Determined Contributions (NDCs) every five years, outlining their specific plans and targets for reducing greenhouse gas emissions. In alignment with these commitments, several nations, including the United Kingdom, have started to incorporate international aviation emissions within their NDC targets, recognizing the importance of addressing emissions from the aviation sector in their overall climate action efforts.

- **ICAO:** In October 2022, member states of ICAO came together to adopt a collective long-term global aspirational goal (LTAG) of achieving net-zero carbon emissions from international aviation by the year 2050. This ambitious target signifies a shared commitment to significantly reduce and ultimately eliminate carbon emissions from the aviation sector to mitigate climate change impacts. To support the realization of this goal, member states also endorsed the new ICAO Assistance, Capacity-building, and Training for Sustainable Aviation Fuels (ACT-SAF) program. This program aims to provide assistance, build capacity, and offer training to facilitate the development and adoption of sustainable aviation fuels, contributing to the broader efforts to decarbonise the aviation industry and achieve the net-zero emissions objective by 2050.

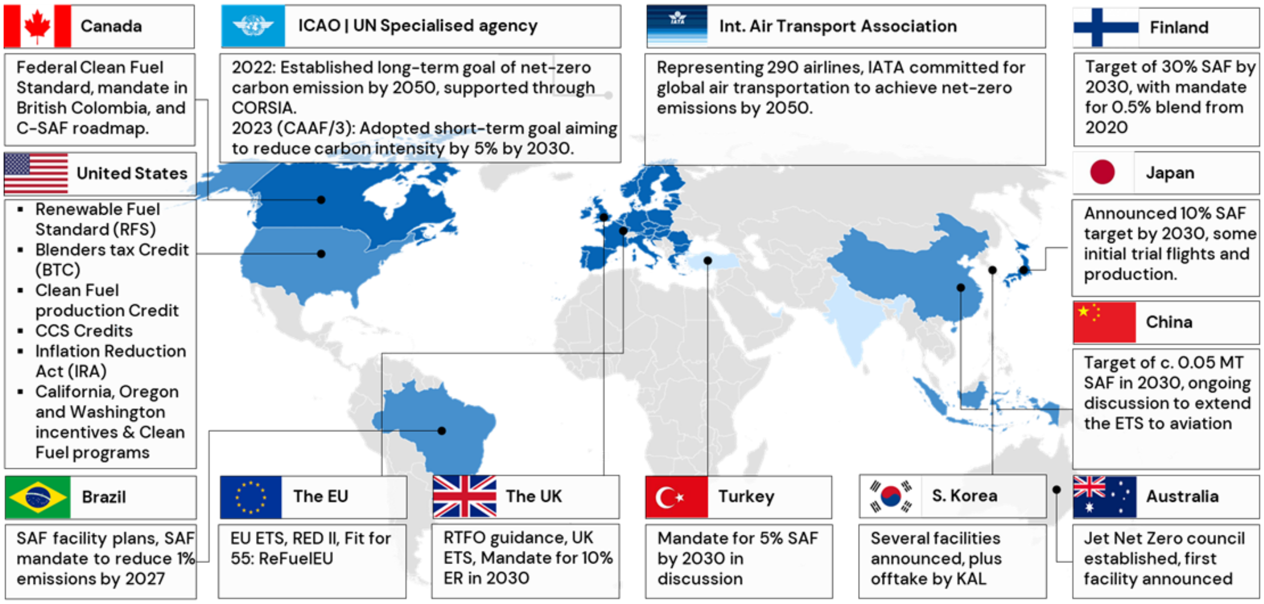
- **CORSIA:** CORSIA is an ICAO initiative designed to achieve carbon-neutral growth in the global aviation sector from 2021 to 2035, with a baseline reference point set at the 2019/20 levels. CORSIA is a widely adopted mechanism for international aviation to align with the goals of the Paris Agreement and mitigate climate change. Participating airlines are required to report emissions data and purchase and cancel 'emissions units' to offset the increase in international CO2 emissions between signatory countries covered by the scheme. Sustainable Aviation Fuels (SAFs) that meet CORSIA specifications, including a minimum greenhouse gas saving threshold of 10% against a fossil fuel baseline, can be utilised by airlines to reduce their CORSIA offsetting obligations. Reporting the use of SAFs and claiming associated emissions reductions will be governed by CORSIA's Standards and Recommended Practices (SARPs) and the accompanying Environmental Technical Manual (ETM). Furthermore, SAFs must demonstrate sustainability through the CORSIA Approved Sustainability Certification Scheme, such as the International Sustainability and Carbon Certification (ISCC) and the Roundtable on Sustainable Biomaterials (RSB), to be eligible for use within the program. Japan is a signatory to CORSIA, obligating the national airlines to comply with this policy.

Global policies

To ensure the effectiveness of SAF policies, they must align with global targets, such as those outlined in the Paris Agreement and the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). This requires a coordinated effort among governments, airlines, and other stakeholders to create a sustainable framework for the production and use of SAF.

The regulatory environment is currently a patchwork, with overlapping regulations in states, countries and internationally. Many countries are introducing SAF policies, with the US, EU, and the UK leading. These policies have typically been built by adjusting existing policies to decarbonise the road industry, although decarbonisation pressures are driving a resurgence, leading to the introduction of new policies specifically to decarbonise aviation. Alongside Japan, ICF is aware of ongoing policy discussions in many other countries, including Türkiye, India, Australia, Singapore, the UAE, and others.

There are many SAF policies and mandates already in place or underway



Source: ICF Analysis, https://www.itf-oecd.org/sites/default/files/docs/sustainable-aviation-fuels-policy-status-report.pdf, https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/policy-net-zero-roadmap.pdf https://www.icao.int/Meetings/a41/Documents/WP/wp_516_en.pdf

The following sections will provide a detailed overview of the policy mechanisms enacted and under consideration in the EU, UK, and US.

Case studies

1. US SAF policies

Available policies in the US

- **Federal programs**
  - The Renewable Fuel Standard (RFS) – SAF typically claims RIN D4 credits
  - The Inflation Reduction Act (IRA)
    - SAF BTC (40B), 2023 to 2024
    - Clean Fuel Production Credit (CFPC - 45Z), 2025 to 2027
    - 45Q and 45V tax credit
- **State level programs**
  - California Low Carbon Fuel Standard (LCFS)
  - Other Low Carbon Fuels (LCF) programs in Washington and Oregon
  - Illinois, Washington, and Minnesota SAF tax credit

The US is leading the SAF industry with both the highest level of ambition and the greatest policy support. The cross-government SAF Grand Challenge aims for 3 billion gallons of SAF (c. 15%) by 2030, and full replacement of fossil fuels with SAF by 2050. The IRA combines with existing federal policy (the Renewable Fuel Standard, RFS) and state-level policies to put this within reach.

The RFS is the backbone of the US biofuel/SAF industry. This policy is a mandate for road fuel users and is predominately met using ethanol from maize/corn. The environmental attributes from SAF can be sold to obligated parties, but fossil jet fuel is not itself an obligated party; therefore this policy acts as an incentive for SAF producers and is ultimately funded by road fuel consumers. Imported fuels are eligible. All biological-derived feedstocks are eligible as long as a 50% greenhouse gas (GHG) reduction is achieved.

State policies complement the federal policies. These include the Low Carbon Fuel (LCF) programs like those in California, Oregon, and Washington, which are mandates to reduce the Carbon Intensity (CI) of the fuel pool. SAF is eligible but not mandated, so these policies also act as incentives for SAF producers, funded by customers using other fuels (e.g. road fuels in California as c. $0.1/gal more expensive due to the policy)

There are new state incentives are developing. The state incentives are likely to be the most important and dynamic area following the passage of the IRA. To date, there are three separate state incentives available in Illinois, Minnesota and Washington state:

- **Washington bill SB 5447 promoting the alternative jet fuel industry in Washington:** This bill provides incentives available for purchases of SAF for flights departing Washington. It is equal to $1 for each gallon of alternative jet fuel that has at least 50% less CO2e than conventional jet fuel and increases by $0.02 for each additional 1% reduction in CO2e emissions beyond 50%.
- **Illinois Sustainable Aviation Fuel Purchase Credit:** This credit is available for every gallon of SAF sold to or used by an air carrier in Illinois. Airlines can claim a credit of $1.50/gallon of SAF that achieves a 50% reduction in GHG emissions and is only available to airlines operating. The incentive is effective for ten years, from June 1, 2023, through June 1, 2033. By 2028, all fuel must be derived from domestic biomass resources.
- **Minnesota Sustainable Aviation Fuel Tax Credit:** The refundable tax credit provides $1.50 per gallon of sustainable aviation fuel produced or blended in Minnesota and sold for use in planes departing Minnesota airports. It further provides a sales tax exemption for construction materials and supplies to support the construction of facilities that produce or blend SAF. The tax credit expires on January 1, 2035.

In August 2022, the US government announced the Inflation Reduction Act (IRA), which introduced specific incentives for SAF. The existing BTC has been modified and the level of support will be calculated based on the Carbon Intensity (CI) score of the SAF, which means more emission reductions will yield higher incentives. The IRA will provide a two-phased approach to incentivize SAF:

- **The first phase, 2023 to 2024:** Starting from 1 Jan 2023, the SAF BTC will provide a $1.25/gal baseline incentive for SAF to achieve a minimum 50% emissions reduction. With increased emissions reduction $0.01 incentive will be provided for each +1% emissions reduction, up to 100%, meaning that SAF demonstrating a 100% reduction will be eligible for the maximum incentive of $1.75 per gallon. To be eligible for these incentives SAF must;
    1. Meet the requirements of ASTM fuel standards,
    2. Be produced from eligible biomass material,

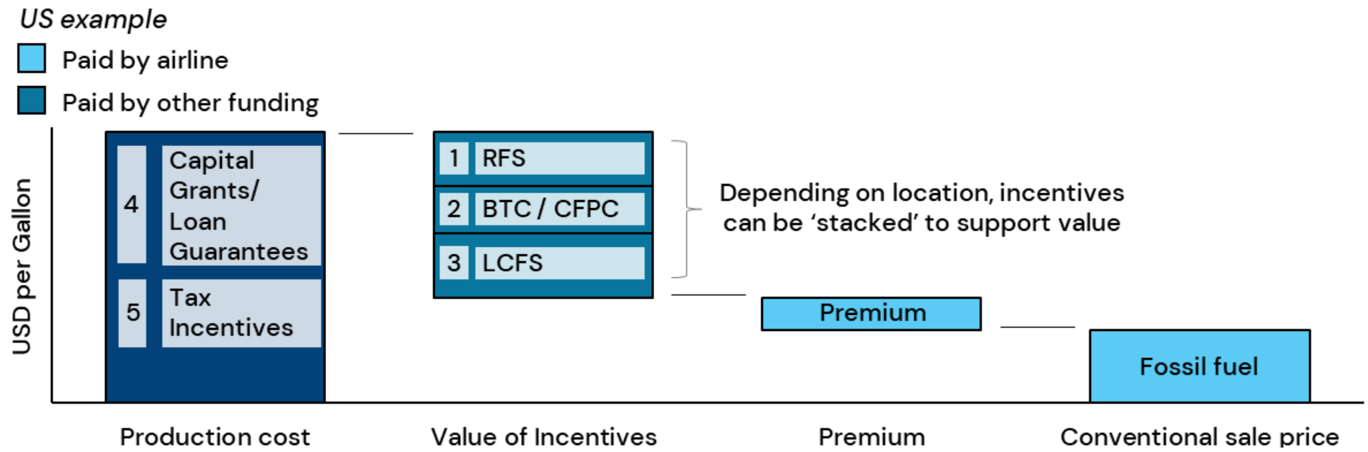
iii. Be certified as having a lifecycle GHG emissions reduction percentage of at least 50% by CORSIA or any similar methodology,

iv. Be blended and sold in the U.S
  - Fuel produced outside the U.S. qualifies if it is blended and sold in the U.S.

- **The second phase, 2025 to 2027:** The SAF BTC will transition to the Clean Fuel Production Credit (CFPC), also known as Section 45Z. The CFPC sets a baseline emissions factor for SAF at 50 KgCO2/mmbtu (approximately 50% reduction), scaling to $1.75/gal for SAF with a 100% emission reduction, and does not appear to be capped so SAF with a negative CI could receive greater value.
  i. The credit can only be earned for the production of fuels in the U.S., so imported SAF is not eligible. However, the fuel does not need to be used in the U.S.
  ii. The credit is earned by the producer of the qualifying fuel rather than the blender. This would be expected to impact how contracts need to be structured to enable the sharing of this value between the seller and buyer of the fuel.
- Additionally, the IRA included two tax credits, the clean hydrogen production tax credit (45V) and the carbon capture and storage credit (45Q).
  i. The 45V tax credit acts as a production tax credit (PTC) for the production of qualified clean hydrogen produced by a taxpayer at a qualified clean hydrogen production facility for 10 years beginning on the date such facility was placed in service. The base tax credit amount is set at $.60 per kilogram of clean hydrogen but increases to $3.00 per kilogram when the hydrogen's lifecycle carbon intensity measures between zero and 0.45 kilograms of CO2 equivalent (CO2e) per kilogram of hydrogen (H2).
  ii. The 45Q tax credit supports the construction of carbon capture facilities. Any carbon capture, direct air capture or carbon utilisation project that begins construction before January 1, 2033, will qualify for the Section 45Q tax credit. The IRA extends carbon capture tax credits through 2033 but also lowers the requirements for additional carbon capture facilities to qualify. The base tax credit for carbon capture by industrial facilities and power plants equals $85 per metric ton for CO2 stored in geologic formations, $60 per ton for the beneficial utilisation of captured carbon emissions and $60 per ton for CO2 stored in oil and gas fields. Additionally, it provides $130-180 per metric ton of CO2 captured through Direct Air Capture (DAC).
  iii. These tax credits can not be claimed together, and cannot be claimed with the CFPC.

SAF in the US can claim multiple incentives, known as 'stacking'. As shown below, a producer could access over $7/gal by selling the physical fuel, claiming the federal RFS and BTC, and selling into California to access the LCFS. This value stack makes the US the most economic region to purchase SAF and has resulted in airlines focusing efforts on geography.

In the US, policy mechanism can be 'stacked', allowing producers to sell SAF close to parity with conventional fuels



Source: ICF analysis

The US also offers a series of grant/loan programs, which are particularly supportive of the developing SAF technologies. The IRA included a $244 million dedicated SAF grant funding through a new U.S. Department of Transportation program. The DOE and other agencies also offer loan guarantees and grant programs, although these can be challenging to access.

Challenges for SAF in the US

The main challenges for SAF in the US are threefold:

- **Timeline:** The SAF incentives under the IRA (BTC and CFPC) will expire in 2027. While they may be renewed, this creates significant policy uncertainty for a key source of revenue for US SAF producers.
- **Funding:** Most SAF support in the US (RFS, LCFS-programs) is funded by road fuel users. With slightly less than half of Americans flying in a typical year, this means many people who don't fly are funding the decarbonisation of the industry. Long-term scaling of the industry may be more challenging as the volume and therefore cost of SAF increases, and this challenge has already led to discussions in California on the possibility of obligation flights within the state within the LCFS.
- **Premium:** A premium of fossil fuel is still required to access SAF in the US, and with no firm demand-signal airlines may limit the additional cost by not scaling to the levels targeted by the Grand Challenges.

2. EU SAF policies

Available Policies in the EU

- **ReFuelEU Aviation**
- **Emission Trading System (ETS)**
- **Energy Taxation Directive (ETD)**

In July 2021, the European Commission announced the Fit for 55 package which included a set of proposals to make the EU's climate, energy, land use, transport and taxation policies fit for reducing net greenhouse gas emissions by at least 55% by 2030, compared with 1990 levels. The package included a recast of the Renewable Energy Directive (RED II), to ensure the EU delivers on their new target by ensuring at least 32% of its energy consumption comes from renewable energy sources by 2030. This also includes a target of a minimum 40% share of RES in final energy consumption by 2030, accompanied by sectoral targets. It also included a proposal called the ReFuelEU Aviation, which introduced a set of policies to decarbonise aviation. The ReFuelEU proposal includes an SAF mandate to support the scaling up of the SAF industry, which will go into effect on January 1, 2025. This mandate applies to all airlines taking off from EU Airports and requires fuel suppliers to supply a minimum share of SAF at EU airports. To avoid European airlines facing a competitive disadvantage due to higher fuel costs pass-through to their customers, airlines will be allowed to claim allowances. A non-compliance penalty has been introduced to ensure mandates are followed across the industry. This mandate will scale up the SAF requirement until 2050, as outlined in the table below.

Table 1: ReFuelEU mandate scale-up

Year	European Commission's proposal	
	Overall SAF Mandate	PtL SAF Sub-Mandate
2025	2%	0%
2030	6%	1.2% (increasing to 2% in 2032)
2035	20%	5%
2040	34%	10%
2045	42%	15%
2050	70%	35%

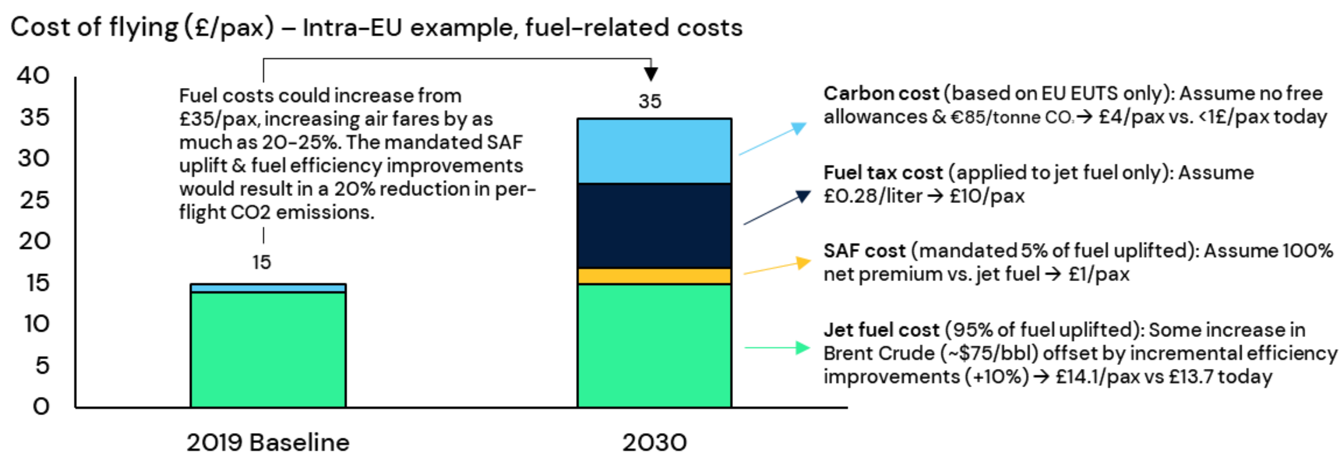
As a part of the package, the Energy Taxation Directive (ETD) is also under revision. The EU ETD aims to align the taxation of energy products and remove outdated exemptions and reduced rates that currently encourage the use of fossil fuels. The revision has not yet been passed.

Feedstock applicable for SAF production is strictly regulated under the EU legislation. SAF is defined as 'drop-in' aviation fuels (fuels substitutable for conventional aviation fuel) that are either synthetic aviation fuels, advanced biofuels produced from feedstock such as agricultural or forestry residues, algae and bio-waste, or biofuels produced from certain other feedstocks with 'high sustainability potential' (used cooking oil, inedible animal fats) that comply with the sustainability and greenhouse gas emissions criteria.

In December 2022, the EU reached an agreement on the EU ETS Aviation reform which paves the way for a faster phase-out of free airline emissions allowances and introduces a system to monitor, report, and verify (MRV) non-CO2 emissions as well as a "SAF allowances" pricing scheme. As a result of this reform, free emissions allowances for airlines covered by the EU ETS will be phased out by 2026 (a year earlier than originally planned), which is expected to increase the operational costs of airlines substantially. Emission allowances will be phased out gradually starting from a 25% reduction in 2024, continuing with a 50% reduction in 2025 and finalizing with a complete phase-out by 2026. Airlines will also need to start reporting non-CO2 effects starting from 2025.

SAF mandates, removal of ETS allowances, and the potential jet fuel tax could meaningfully increase operational costs to airlines. The ICF case study analysis on an intra-European flight suggests that the fuel costs (£/pax) could double by 2030.

Fuel costs may double for a typical short-haul flight in the EU by 2030 mainly as a result of the carbon costs, fuel tax and SAF



Source: ICF analysis

Challenges for SAF in the EU

The main challenge for SAF in the EU is the ability to comply with the mandate levels. There have been limited investments into new capacity in the EU, driven by the following factors:

- **Minimal supply side support:** While the mandate will establish a demand signal, there is currently no supply-side support. Assuming that customers will pay due to the mandate challenges the investment case for SAF facilities, which often cost several billion USD. This may change, with the EU announcing a potential program to close the price gap using funding from the ETS revenues.
- **Constrained feedstocks:** Essentially all investment in the EU has been in HEFA capacity as this will likely be the cheapest approach to comply with the mandate. This technology requires feedstocks such as UCO and tallow, which are in short supply globally. Competition from the US and other demand centres that may evolve in other countries will drive up the cost and availability for these feedstocks.
- **Policy uncertainty:** The policies are yet to be established and have been delayed several times. This leaves very little runway to get capacity built, with just 1.5 years until the mandate start compared to a more typical 2-5 years to plan, build and commission facilities.

3. UK SAF policies

Available Policies in the UK

- **SAF Mandate, in place from 2025**
- **SAF Facility grant funding**
- **UK ETS**
- **RTFO (Obsolete after mandate implemented)**

The UK government has committed to scaling the use of SAF to achieve its "2050 Jet Zero target", announced in July 2022. As part of this strategy, by 2025 the UK has committed to have at least five UK SAF plants under construction and a SAF mandate in place with a target of 10% SAF by 2030 (equivalent to 1.2 million tonnes), with a carbon intensity mechanism, allowing SAF with higher emissions reductions to contribute more to the goal.

The UK government has allocated £180 million in funding for the SAF industry by 2025, which is incremental to the Advanced Biofuels Demonstration Competition (ABDC, 2014, £25m), Future Fuels for Flight and Freight Competition (F4C, 2017, £22m) and Green Fuels Green Skies Competition (GFGS, 2021, £15m) funds that supported the development and commercialization of SAF pathways.

In March 2023, the UK government released the second SAF Mandate Consultation, detailing the proposals to design and implement an SAF mandate. The paper presented proposals for volumes (via blending ratios), buy-out prices, details on the PtL SAF sub-mandate, and a HEFA cap. The mandate will start in 2025 and will establish targets through 2040. Once the mandate is implemented, SAF will no longer be eligible for the RTFO.

- **SAF Mandate:** The paper proposes a standard obligation, which can be met using "standard SAF", and a sub-mandate for PtL SAF. While the sub-mandate design is similar to the EU's approach, the PtL SAF mandate is notably less ambitious.

Table 1: UK SAF mandate scale-up

	2025		2030		2035		2040	
	Standard SAF	PtL SAF	Standard SAF	PtL SAF	Standard SAF	PtL SAF	Standard SAF	PtL SAF
Low	0.5%	0%	10%	0.05%	13%	0.25%	17%	1.5%
Med	2%	0%	10 %	0.10%	15%	0.50%	22%	3%
High	4%	0%	10%	0.20%	18%	1%	32%	6%

- **Sustainability criteria**: SAF must achieve at least 50% greenhouse gas (GHG) savings relative to fossil jet fuel, which will increase over time.

- **Feedstocks**: Waste/residue feedstocks can be used but food/feed crops and energy crops are excluded. For the PtL sub-mandate, CO2 from the atmosphere, biological sources and fossil sources can be used. While the EU suggests that fossil CO2 will not be eligible after 2035, the UK Proposal does not suggest a similar cap. Hydrogen needs to be produced using electricity generated from renewables or nuclear (Blue hydrogen is currently excluded and would require legislative change to include).

- **HEFA cap**: HEFA contributes to the standard obligation, but can only be used up to a cap. The proposal suggests a wide but low range for the HEFA cap, from 0 to c. 0.2 million tonnes (Mt) in 2030. For context, the total 2030 mandate is expected to be around 1.2 Mt.

- **Buy-out price:** The UK is proposing a fixed buy-out price (compared to the EU proposal of a buy-out price as a multiplier of the premium).

Table 2: UK SAF mandate buy-out price options

	Buy-out price options	
	Standard SAF (£/tonne)	PtL SAF (£/tonne)
Low	£ 2,051	£ 2,567
Medium	£ 2,567	£ 3,525
High	£ 3,846	£ 5,320

- **Carbon intensity (CI) mechanism**: The proposal suggests a mechanism to scale certificates awarded by the CI factor. SAF with a lower CI score, would generate more certificates. This would increase the certificates awarded if they are higher/lower than an 'average' SAF value, proposed at 26.7 gCO2e/MJ (a 70% GHG reduction). It suggests either a continuous calculation or using a bands approach. For example, using the 'banded' approach, SAF achieving a 50% GHG reduction would receive 0.79 certificates, while SAF achieving a 100% GHG reduction would receive 1.36 certificates.

- **Tradable certificates**: The proposal suggests the compliance certificates will be tradeable. This means that the mandate could be met with geographically variable use of SAF, with some airports using large volumes and others using none.

The UK ETS supports SAF by increasing the cost of fossil jets. While the UK ETS trades with an illiquidity premium to the EU ETS due to the smaller volumes, the value is still insufficient to make SAF use viable without other measures.

Challenges for SAF in the EU

The main challenges for SAF in the UK are the ability to comply with the mandate level and specific sustainability criteria. No new facilities in the UK have passed the Final Investment Decision (FID), driven by several factors:

- **HEFA Cap:** While the EU has heavily invested in HEFA and co-processing capacity, the UK HEFA cap has held back any major investments in this approach - compounded because the level of the cap has yet to be announced. The rationale for this approach is to avoid the substitution of feedstock from renewable road fuels (via the RTFO). This drives the UK to technologies such as Fischer-Tropsch, and cellulosic ethanol to jet, and while these are potentially more sustainable and scalable, their high cost and lower technical maturity make the investment case significantly more difficult.
- **Minimal supply-side support:** While the UK has several facilities in reasonably advanced stages of planning (stimulated through the grant funding), these plants cannot be financed/built without policy and revenue certainty. While the government has discussed several mechanisms (with industry coalesced around a CfD), no decision has been made. ICF understand that a key stumbling point is funding, with the government seemly unwilling to hypothecate revenue from the APD or ETS, and suggesting any mechanism would require additional funding, presumably from the aviation industry.
- **Timelines:** The mandate is still under consultation, no supply-side policy has been established, and non-HEFA facilities are more complex and will require several years to design, build, and commission. The non-existent availability of compliant SAF for import by 2025 suggests that any shortfall will need to be bought-out from, resulting in airlines incurring cost while achieving no emission reduction.

3 SAF policy development framework

SAF policy framework considerations

To stimulate domestic SAF production, METI further announced plans to (1) develop a capital investment subsidy program, (2) exempt imported SAF from the fossil fuel import tariff, and (3) support research, development, operation, and certification acquisition. To successfully develop policies to support METI's plan, it is crucial to consider the guidance document developed by ICAO on the importance of SAF policies for the deployment of SAF, 'Guidance on potential policies and coordinated approaches for the deployment of sustainable aviation fuels'.[159] This document states that long-term, stable policies are necessary to create a sustained market for SAF.

According to ICAO, policy mechanisms can:

1) Stimulate the growth of the SAF supply through research and development (R&D) investments and financing;
2) Create SAF demand via mandates, subsidies, and commitments; and
3) Enable the SAF market via standards.

Policy effectiveness as well as options to simulate the growth of SAF supply and to create a demand for SAF are detailed further in the following sections.

1. Policy effectiveness metrics

To determine whether a policy is effective, feasible, and practical, ICAO identified several metrics to serve as a guideline.

Table 1: Policy effectiveness metrics

Metric	Description[160]
Flexibility	Flexible policies can adapt to various situations and priorities, while rigid policies have limited flexibility and can only be altered by high-level authorities over the long term.
Certainty	These characteristics involve timeframes, legal conditions, and political decisions. Policy certainty is crucial for investors and stakeholders, as it affects the economic value and security of investors. Greater policy certainty enhances the attractiveness of capital investment, while lower certainty has the opposite effect. Medium to long-term policy certainty sets investor expectations and increases investor interest
Financial costs and benefits	Policy effectiveness should evaluate costs, benefits, and social costs, especially for policies relying on government financial support, assessing their alignment with stated objectives.
Ease of implementation	Policy implementation can be hindered by administrative, governance, and procedural challenges, especially when multiple agencies are involved. States should clarify the roles of local, regional, and national jurisdictions to prevent barriers and ensure effective policy governance.
Contribution to SAF deployment and GHG reduction	Policies should set clear criteria on the target quantity of SAF to be deployed, sustainability achievement, commercial

[159] ICAO – Guidance on potential policies and coordinated approaches for the deployment of sustainable aviation fuels
[160] ICAO – Guidance on potential policies and coordinated approaches for the deployment of sustainable aviation fuels

	parameters, and timeframe. Incentivizing higher GHG reduction and considering social and economic consequences can enhance policy effectiveness compared to environmental-focused policies.
Unintended consequences	Effective policies must consider and mitigate the risk of unintended consequences, which can be economic, environmental, or social, through suitable mechanisms.
Robustness of policy	Policy effectiveness is influenced by its robustness, which involves a regulatory system to ensure objectives are achieved and proper procedures are followed post-implementation.

2. Stimulating the growth of the SAF supply

To catalyze the growth of SAF feedstock and production capacity, a recommended policy approach involves strategic measures. Firstly, government funding should be allocated to SAF research, development, demonstration, and deployment, accelerating the learning curve and fostering innovation. Secondly, targeted incentives and tax relief mechanisms should be implemented to encourage the expansion of SAF supply infrastructure, ensuring a robust and widespread network. Thirdly, providing support for the operational costs of SAF facilities is essential to bolstering their viability and sustainability. Finally, recognizing and valorizing the environmental benefits of SAF plays a pivotal role in incentivizing further developments in this sector, reinforcing the importance of aligning policies with the broader goal of sustainable aviation.

These policy options collectively foster growth and innovation and are supported by the following policy options.

Table 2: Policy options targeted at stimulating the growth of SAF supply

Policy Option	Description[161]
Capital Grants	A government grant is given to an entity to build or buy SAF-specific infrastructure. Capital grants reduce the financial needs and financial risks of the targeted investment. (e.g., US Department of Energy (DOE) Loan Program Office)
Loan Guarantee Programs	A loan backed by a government institution helps the project's financial case and also reduces overall project risk, making acquiring additional equity of debt easier and lowering the cost of capital.
Business Investment Tax Credits (ITC)	An ITC allows the deduction of construction and/or commissioning costs of a qualifying asset which can reduce income tax payable and flow through the investors.
Blending Tax Credit (BTC)	An incentive targeted at the providers or blenders of fuel that provides a credit against taxes. This mitigates the blender's

[161] ICAO – Guidance on potential policies and coordinated approaches for the deployment of sustainable aviation fuels

	cost of production or purchase difference between SAF and fossil jet. (e.g., US State-level BTC in Illinois and Washington)
Production Tax Credit (PTC)	An incentive targeted at the producers of fuels that provides a credit against taxes. This mitigates the cost of production difference between SAF and fossil jet. (e.g., US Inflation Reduction Act (IRA) Clean Fuel Production Tax Credit (CFPC))
Recognizing SAF benefits under carbon taxation and cap-and-trade systems	Where a jurisdiction has introduced a carbon tax, carbon price, or carbon levy, SAF could be rated as either zero or in proportion to the life-cycle greenhouse gas emissions benefit of the particular fuel, thereby subject to reduced tax. This differs from a cap-and-trade system by not stipulating an overall emission reduction target.

3. Creating SAF demand

To develop the demand for SAF, a multi-faceted approach is recommended, encompassing the following:

- The creation of SAF mandates
- The revision of existing policies to integrate SAF, and;
- The demonstration of government leadership.

These policy options collectively aim to encourage increased SAF utilisation within the transportation fuel supply. Strategies include enforcing mandates that require a certain proportion of SAF in aviation fuel, updating current policies to encompass SAF applications, and fostering voluntary commitments from stakeholders in support of SAF adoption.

Table 3: Policy options targeted at creating demand for SAF

Policy Option	Description[162]
Mandate renewable energy volume in the fuel supply	An obligation on fuel providers to provide increasing SAF volumes added to the existing fuel supply on a multi-year schedule creates an incentive for the production of more SAF and other fuels which meet the renewable energy definition of the program. (e.g., the EU's Renewable Energy Directive (RED) and US Renewable Fuels Standard (RFS))
Mandate reduction in carbon intensity of the fuel supply	An obligation on fuel providers to reduce the carbon intensity (life-cycle greenhouse gas emissions intensity) of the transportation fuel supply on a multi-year schedule creates an incentive for the production of more SAF and other fuels with greenhouse gas benefits. (e.g., California Low Carbon Fuel Standard (LCFS))
Policy statement to establish direction	Setting aspirational goals for a specific production or use amounts to signal future intent to develop comprehensive SAF policy measures. This can be linked to the

[162] ICAO – Guidance on potential policies and coordinated approaches for the deployment of sustainable aviation fuels

	implementation of future policies, sending a signal for project planning. (e.g., US SAF Grand Challenge)
Corporate commitment to SAF use	A strong demand signal can be created by requiring corporations to commit to renewable fuel/SAF procurement to reduce the impacts of air travel and operations.
Stakeholder/Customer pressure	Policy certainty and the requirement to decarbonise operations are typically important to stakeholders and customers to continue their investment.

4. Enabling SAF markets

Further actions may be required to establish the transparency and confidence necessary for the optimal operation of SAF markets.

Table 3: Policy options for enabling SAF markets

Policy Option	Description[163]
Adopt clear and recognized sustainability standards and life cycle GHG emissions methods for certification of feedstock supply and fuel production	The use of clear standards and harmonized methods for life cycle GHG emissions calculation and sustainability certification will support broad SAF markets and ensure environmental integrity.
Support development/recognition of systems for environmental attribute ownership and transfer	Standard processes and shared systems for calculating, crediting, and trading the environmental attributes of SAF may facilitate "book and claim" purchasing of SAF that decouples the physical fuel location and the environmental benefit to facilitate and promote more efficient and broader use of SAF volumes and their GHG emission reductions.
Support SAF stakeholder initiatives	Stakeholder consultation groups can take many forms and be either government, industry or NGO-led. These groups serve a critical function of aligning the diverse stakeholders that make up the SAF supply chain. They can directly coordinate actions and provide critical information and feedback to policymakers.

4 Policy opportunity in Japan

Overview of SAF policy developments in Japan

The long-term adoption of SAF is a key component of the Government of Japan's (GOJ) plan to increase the utilisation of biofuels in the transportation sector and to support their overarching goal to reduce greenhouse gas emissions in their aviation sector. To realise this goal, MLIT and METI jointly launched a public-private

[163] ICAO – Guidance on potential policies and coordinated approaches for the deployment of sustainable aviation fuels

partnership to facilitate the development of reliable domestic production of SAF. Council members include government agencies, oil refineries and retailers, airlines, airports, oil storage, plant design, trading houses, and related industry associations.

As a result of this partnership, MLIT published the draft Basic Policy for Promoting Decarbonisation of Aviation in October 2022. MLIT outlines three targets for airlines:

1) Stabilization of CO2 emissions from international flights
2) Reduction in CO2 emissions per unit transport from domestic flights by 16% by 2030
3) Carbon neutrality for both international and domestic flights by 2050

Additionally, METI published a draft interim report[164] on SAF introduction in Japan. This report calls for Japanese SAF producers and suppliers to establish sufficient SAF manufacturing capacity and secure raw materials to produce SAF sustainably and at competitive prices[165]. To stimulate domestic SAF production, METI announced plans to set a new target volume for SAF under the 'Act on Promotion of Use of Non-Fossil Energy Sources and Effective Use of Fossil Energy Raw Materials by Energy Suppliers' by 2030. METI based this target volume on the Basic Policy for Promoting Decarbonisation of Aviation, aiming to replace 10 per cent of jet fuel consumption with SAF by 2030. MLIT estimates that if SAF achieves this target, SAF demand will reach 1.7 billion litres per year.

Unlike the pessimistic outlook for Japan's on-road biofuel demand, the GOJ foresees SAF as an opportunity to expand Japan's liquid biofuel demand. Japan's biofuel target for transportation was recently updated. METI proposed to maintain the annual target volume for transport biofuels at 500 million litres of crude oil equivalent (LOE), with both bio-ethanol and sustainable aviation fuel eligible to count to meet the target. Additionally, certain feedstocks will allow the derived SAF volume to count twice.

Existing SAF funding mechanisms

As part of Japan's goal to achieve carbon neutrality by 2050, METI has established a substantial Green Innovation Fund with a budget of 2 trillion yen (USD 16 billion), as part of the Fiscal Year 2020 Tertiary Supplementary Budget. This fund is entrusted to the New Energy and Industrial Technology Development Organization (NEDO) for its administration and operation. The primary objective of this fund is to provide steadfast support to companies and other organizations committed to embracing ambitious targets for 2030, which have been collaboratively set by both the public and private sectors. This support spans the entire spectrum, ranging from research and development (R&D) efforts to practical demonstrations and the societal implementation of innovative solutions over the next decade. These target areas have been carefully selected based on their potential for significant policy impact and the necessity of sustained, long-term support to realize their widespread adoption.

[164] https://www.meti.go.jp/shingikai/energy_environment/saf/pdf/003_07_00.pdf

[165] https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=METI%20to%20Develop%20a%20Separate%20SAF%20Target_Tokyo_Japan_JA2023-0050.pdf

As part of this fund, NEDO awarded 114.5-billion-yen (USD 916 million) grants to pilot projects developing e-fuel, SAF and other green fuels.

Carbon credit mechanisms

The Government of Japan (GOJ) administers two carbon credit certification programs, namely the J-Credit System for domestic activities and the Joint Crediting Mechanism (JCM) for international activities. Both initiatives were inaugurated in 2013. Under the domestic program, known as the J-Credit System, METI, MAFF, and MOE collaborated to establish and manage a carbon market. This system is designed to bolster regional efforts to reduce greenhouse gas emissions. It's noteworthy that J-Credits may be applicable within the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), despite CORSIA's offsetting not being voluntary and necessitating corresponding adjustments.

Principles for successful SAF policy in Japan

The SAF industry in Japan is still in its early stages, and the success of different policy approaches is yet to be proven. It is crucial for policies to address the existing challenges faced by the SAF industry in Japan. These challenges include:

- **Non-binding target:** The ambition for 10% SAF by 2030 represents a target, rather than a mandate. ICF understands from discussions with local stakeholders that the social obligation created by this target will drive many companies, particularly those based locally, to increase SAF use. However, it lacks many of the important details of a mandate, such as a non-compliance penalty, sustainability criteria, and trajectory beyond 2030.
- **Limited feedstock availability:** There is relatively limited feedstock in Japan compared to the size of the aviation industry, and the high cost of land and labour may make it more economical to develop production in other countries and then import the SAF. This may directly impact Japan, with several companies investigating opportunities across the country.
- **Supply vs. demand:** The relationship between fuel suppliers and airlines relies on regulatory authorities to provide guidelines, and determine the SAF market drivers, rather than building a symbiotic relationship for creating demand for SAF and providing SAF supply based on the set government target.
- **No clear CAPEX or OPEX support:** While several options are under consideration, no support has yet been announced. This may hold back investments in SAF facilities in Japan.

To address the challenges faced by the sustainable aviation fuel (SAF) industry in Japan, several policy trends can be observed across the leading countries. These trends include the following:

- **Developing a strategic goal:** Successful SAF policy hinges on the development of a strategic goal. This includes considerations such as the country's decarbonisation targets, the desired volume of SAF production, and the associated economic and environmental impacts.
- **A combination of mechanisms is required:** Every country with meaningful progress on SAF has adopted a combination of policies, with each addressing a different challenge**.** Most countries have a range of demand mechanisms (the mandate in the UK, EU, and Grand Challenge in the US), complemented with supply mechanisms (the IRA in the US, revenue support in the UK, and ETS fund in

the EU). The EU and UK are further using the ETS to close the cost gap, while the US has adopted much more generous supply-side mechanisms to bring SAF prices closer to parity with fossil fuels. These combinations are both more effective than isolated policies, and also provide a measure of policy redundancy, mitigating the impact for investors if one of the policies is removed or altered.

- **Clear policy over longer durations:** Policy uncertainty holds back policy investment, with financers waiting for clarity and enforcement before deploying the considerable value required. The impact can be seen in the UK, where no greenfield facilities have achieved FID despite the progress made on policy. Longevity of policy is also crucial given the long timeframes that SAF facilities will operate over, and the uncertainty over the renewal of the CFPC credits in the US IRA has been cited by several companies as a reason to avoid investment.

- **Grants to kick-start the market:** Every country developing SAF has made use of grant mechanisms to de-risk early facilities, including the IRA funds in the US, AFF in the UK, MS funds in the EU, and GX fund in Japan. These have generally been awarded to support the developing (non-HEFA) technologies.

- **Sustainability standards:** The US, EU, and UK have all established sustainability standards with a higher floor level than CORSIA, by requiring higher GHG reductions. In the US, several policies (LCFS, BTC, CFPC) directly link the credit value to the CI of the fuel, and the UK has proposed a mechanism to increase the mandated value for fuels with a lower CI.

- **Market for co-products:** Every SAF facility produces a range of products, and the commercial case for SAF facilities typically leverages domestic value for the renewable diesel and naphtha produced. For example, renewable diesel can claim the RFS, LCFS, and BTC value in the US, RED II compliance in the EU, and the RTFO in the UK, providing a meaningful contribution to the commercial case for an SAF facility. These existing renewable fuel industries also ensure access to a skilled workforce, and knowledgeable investors, insurers, and engineers. Attracting and building these skills may require additional time and value compared to more developed markets.

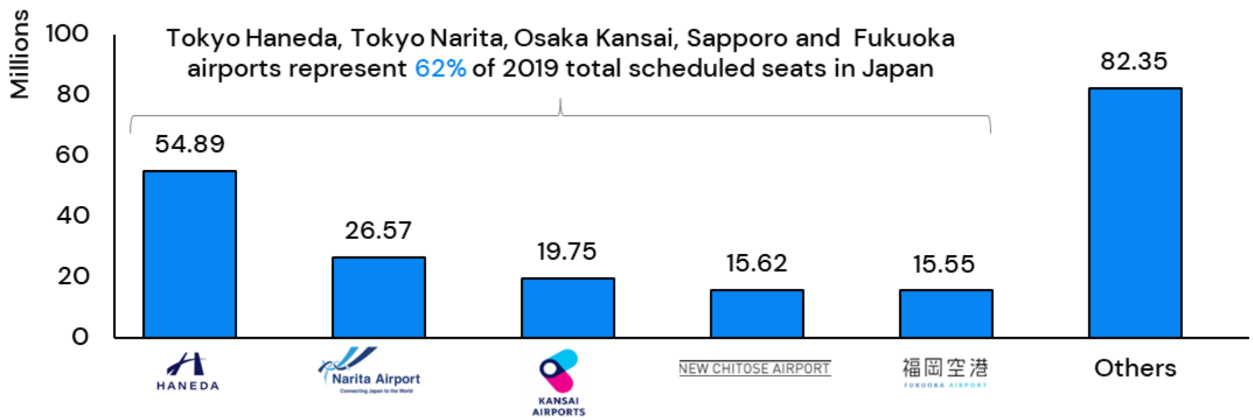
5 Policy impact analysis

Price disparities in aviation fuel can adversely affect airline operators' financial performance, undermine market competition, and result in higher fares for consumers, reducing regional connectivity and business competitiveness in the aviation sector. Due to the price premium airlines must pay for SAF (compared to conventional jet fuel), implementing a mandated SAF target with no additional mechanisms to reduce the cost-pass through to airlines and passengers could put transiting passengers and associated revenue at risk.

To understand the potential risk of the 10% SAF target, ICF conducted a risk analysis. For context, the Japanese aviation industry is reasonably concentrated with 62% of scheduled seats concentrated in the top 5 airports.

The top 5 airports in Japan represent over 60% of total scheduled seats in Japan

Total scheduled seats by Japanese airports, 2019



Source: ICF analysis, OAG data

The market is dominated by local passengers and point-to-point traffic, which provides a degree of resilience to cost increases. Although the Shinkansen provides strong competition on short routes, many routes cross the ocean with few direct alternatives. At the top 5 airports, only 12.5% of passengers are connecting. However, this portion is focused on Haneda and Narita, with 18.4% and 15.7% connecting passengers respectively. While many are domestic to domestic (D-D) and not at risk of substituting to foreign airports, a non-negligible portion are domestic to international (D-I) or international to international (I-I) and could feasibly connect via alternative hubs.

Table 1: 2019 passenger transfers across Japanese airports

Data	Haneda	Narita International Airport	Kansai Airports	New Chitose Airport	Fukuoka Airport
Total scheduled seats	54,891,639 (Total actual PAX: 41.2M)	26,568,724 (Total actual PAX: 22.2M)	19,748,881 (Total actual PAX: 16M)	15,617,989 (Total actual PAX: 11.9M)	15,552,319 (Total actual PAX: 12M)
% of Japan scheduled seats	26%	12%	9%	7%	7%
Number of local pax	33,992,952	18,685,268	15,282,284	11,334,081	11,493,987
% of local pax	81.6%	84.3%	95.7%	95%	95.7%

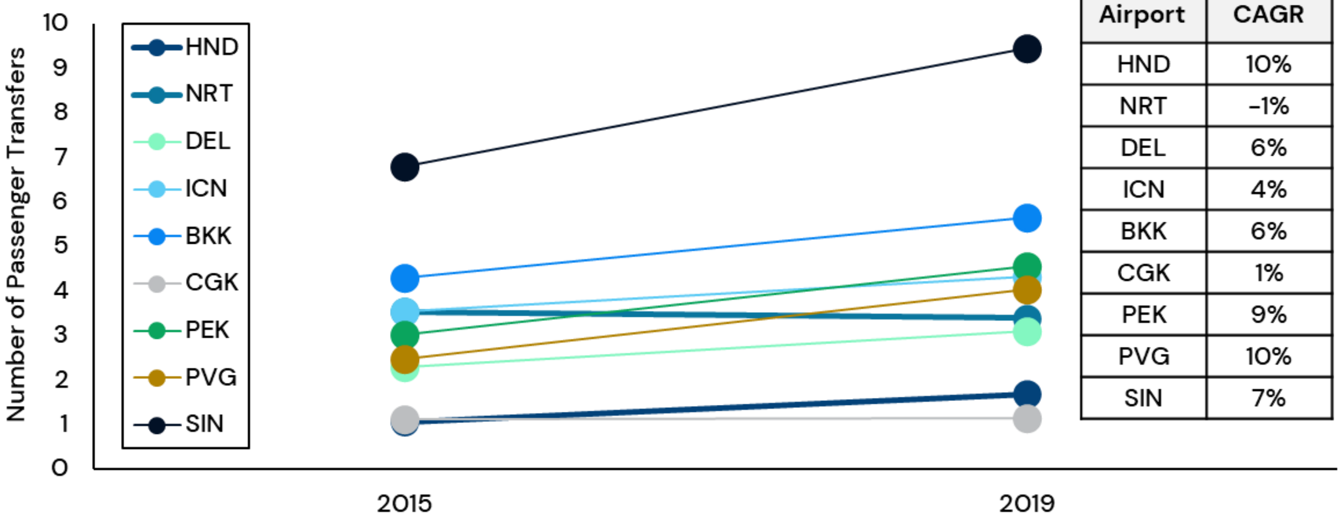
Number of total transfer pax (D-D, D<>I, I-I)	7,648,220	3,471,873	681,214	592,461	522,322
% of total transfer pax (D-D, D<>I, I-I)	18.4%	15.7%	4.3%	5%	4.3%
Number of non-domestic transfer pax (D<>I, I-I)	1,686,609	3,325,691	467,572	47,343	65,812
% of non-domestic transfer pax (D<>I, I-I)	4%	15%	3%	0,4%	0,5%
Number of international-international transfers	210,784	1,795,352	95,817	1,110	1,895
% of international-international transfers	0.5%	8.1%	0.6%	0.01%	0.02%

PAX = Passengers

There is growing competition from regional hubs. Seoul (ICN), Singapore (SIN), and Shanghai (PVG) are all located within a few hours of flight time, and all three have aggressive expansion plans. Beijing is opening a new airport (PKX) in the same radius. All have significantly increased their share of transfer passengers (PVG+10%, ICN+4%, SIN+7%, PEK+9%), and while Haneda (HND) increased by +10%, Narita (NRT) (which has significantly the largest transiting pax share in Japan) dropped by -1%.

PVG and SIN have increased their passenger growth between 2015 to 2019, and provide the highest threat for passenger spillage to Japanese airports

Total scheduled seats by airports in Japan, 2019, Millions



Airport	CAGR
HND	10%
NRT	-1%
DEL	6%
ICN	4%
BKK	6%
CGK	1%
PEK	9%
PVG	10%
SIN	7%

Source: ICF analysis, OAG data

Transiting passengers is a small (12.5%) but valuable segment for Japanese airlines/airports. Approximately 5% could use alternate airports, representing 14% of revenues. Other regional hubs (PVG, ICN, SIN, PEK) are increasingly becoming gateways to the Asian market, increasing competition for valuable transfer passengers. Implementing the Japanese 10% SAF target with no additional mechanisms to reduce the cost pass-through to airlines/passengers would put many of these transiting passengers and associated revenue at risk.

Table 2: Key Asian airports and their respective SAF discussions

Country	Airport Code	PAX Number (2019)	Distance to HND	Airport expansion projects	SAF Policies
China	PEK	100m	1,299 mi (2,091 km)	No Expansion Project released on this airport but the opening of New Airport PKX (100mppa)(I)	No SAF mandates or policies to date. Working on SAF development, exploring partnerships with research institutions and industry players for sustainable aviation solutions. In 2011, China's regional carbon emission trading systems were launched in seven provinces and cities. Shanghai is the only one to
	PVG	76m	1,079 mi (1,737 km)	Initiation of expansion project 4th phase, new T3 expected 50m additional pax (II)	
	HKG	71m	1,802 mi (2,900 km)	The current expansion project transforms the airport into 3 runways system+ that expands T2 by 2024 (III)	

Country	Airport Code	PAX Number (2019)	Distance to HND	Airport expansion projects	SAF Policies
	CAN	73M	1,792 mi (2,884 km)	Phase 3 expansion to start in 2023 + creation of new international airport (120m pax expected) (IV)	have included the aviation sector, but the Chinese government aims to do so by 2025. (1)
Korea	ICN	71M	751 mi (1,210 km)	Phase 4 is to be concluded in 2024 including expansion of Terminal 2, additional runway and access and operation improvements (V)	No SAF mandates or policies to date. Regulators want to frame a SAF policy in the upcoming years and are using Korean Air to test SAF at scale. ICN is the first Asian airport to join RE100 (100% renewable energy), enabling the airport to largely cut its Scope 1 and 2 emissions. It is also currently improving its infrastructure for future SAF supply. (2)
Singapore	SIN	68M	3,292 mi (5,299 km)	The expansion project includes the construction of T5 (+50m pax) and transformation into 3 runways system by mid-2030 (VI)	No SAF mandates or policies to date. Singapore Government is working on a Sustainable Air Hub Blueprint, due to be published in 2023, that should provide guidelines towards SAF incentives or mandates (3) Civil Aviation Authority of Singapore partners with SIA and global investment firms to develop SAF credit usage, to incentivize SAF utilisation (4) The airport is supporting a one-year trial which will see Singapore Airlines and Scoot purchase 1.25 million litres of neat SAF delivered

Country	Airport Code	PAX Number (2019)	Distance to HND	Airport expansion projects	SAF Policies
					through the airport fuel system. [(5)]
Thailand	BKK	65M	2,862 mi (4,607 km)	East Expansion Project is a $236m expansion starting from July 2022 and to be completed in 2025 that will increase capacity by 44% up to 65m [(VII)]	No SAF mandates or policies to date. The government is showing interest in SAF development and evaluating its feasibility within the broader context of its sustainability goals. However, the country is only starting to measure its emissions and no policy/regulation/mandate or incentive has yet been published [(6)] Some Thai companies like Energy Absolute or Bangchak Corporation are investing in SAF
India	DEL	68M	3,632 mi (5,845 km)	IGI to become the only Indian Airport with 100m+ capacity. These projects include expanded T1 and T3, construction of a fourth runway, new T4 [(VIII)]	No SAF mandates or policies to date. Exploring options for SAF production and deployment to address environmental concerns and promote greener aviation practices. India has the feedstock potential to produce sufficient SAF for 50% blending of current aviation. [(7)]
Indonesia	CGK	54M	3,586 mi (5,772 km)	Creation of Terminal 4 to bring total capacity to 100m+ pax. The project of	No SAF mandates or policies to date. SAF development program in Indonesia, but no

Country	Airport Code	PAX Number (2019)	Distance to HND	Airport expansion projects	SAF Policies
				the new airport was abandoned. (IX)	mandate announced to date. Garuda Airline tested SAF on its aircraft in mid-2023 from Palm Oil feedstocks (8)

Sources: Pax number from Airport Council International, Airports annual reports and Websites. Country regulator guidelines, distances from Great Circle Mapper, (I), (II), (III), (IV), (V), (VI), (VII), (VIII), (IX)
(1), (2), (3), (4), (5), (6), (7), (8)

6 Closing statement

Decarbonising Japan's aviation industry in less than three decades is challenging but achievable. Commercial aviation has barely existed for a century, and yet in that time has progressed at a rapid pace, with Whittle inventing the jet engine just 27 years after the first powered flight, and Concorde carrying passengers at supersonic speed only 46 years later. Recent improvements have been less noticeable but perhaps more revolutionary, with efficiency improvements making flights affordable to millions more people and decoupling emissions from the industry growth.

The industry must continue to evolve. In just 26 years, by 2050, aviation should replace the polluting fuels currently used with clean energy to avoid the worst impacts of climate change. Accelerated efficiency improvements will be critical to ensure as little energy as possible is required, but this must be matched by a very rapid build-out of the SAF industry.

This analysis shows that considerable feedstock can be accessed in Japan, with the capacity to produce 11 million kilolitres (2,906 million gallons) SAF by 2050. This is adequate for Japanese aviation to achieve its decarbonisation goals, succeeding through a portfolio of efficiency, net zero aircraft, SAF, and out-of-sector measures. While SAF is currently more costly to produce than fossil fuels, it also provides much more value – most prominently through reduced emissions, but also by enabling job and economic growth, and increasing the resilience of Japan's energy supply.

The Air Transport Action Group (ATAG) Waypoint 2050[166] report estimates that the global aviation industry will require approximately 400 million tonnes of SAF by 2050. The report emphasizes that the companies and intellectual property (IP) required to achieve even half of this volume will be significant drivers of the future economy. This is an area Japan has shown leadership in previously, with exports of equipment and machinery providing an estimated revenue of 40 trillion yen to Japan every year.

The global SAF policy environment is developing at pace, led by the US, EU, and UK. Japan has a solid foundation to join these pioneers, with adequate feedstocks, expertise, and abundant enthusiasm. Efficient and transparent policies to support both the demand and supply side of the industry represent the final catalyst to develop a SAF ecosystem in Japan, and their evaluation and implementation represent the most important next steps for the industry.

[166] https://aviationbenefits.org/environmental-efficiency/climate-action/waypoint-2050/

Photo by Eva Bronz

Appendix

CORSIA Sustainability Criteria for SAF[167]

To be eligible under ICAO's CORSIA, SAF needs to meet the following principles of sustainability across its supply chain:

Sustainability Criteria	Principle
1. **Greenhouse Gases (GHG)**	SAF should achieve a life cycle emission reduction of at least 10% compared to the baseline life cycle emissions of 89 grams of CO2 equivalent per megajoule
2. **Carbon stock**	SAF should not be made from biomass obtained from land/aquatic systems with high biogenic carbon stock (i.e. forests, wetlands, or peatlands)
3. **Greenhouse gas emissions reduction permanence**	Emissions reduction attributed to SAF should be permanent
4. **Water**	Production of SAF should maintain or enhance water quality and availability
5. **Soil**	Production of SAF should maintain or enhance soil health
6. **Air**	Production of SAF should minimize negative effects on air quality
7. **Conservation**	Production of SAF should maintain biodiversity, conservation value, and ecosystem services
8. **Waste and Chemicals**	Production of SAF should promote responsible management of waste and use of chemicals

[167] https://www.icao.int/environmental protection/CORSIA/Documents/CORSIA_Eligible_Fuels/ICAO%20document%2005%20-%20Sustainability%20Criteria%20-%20November%202022.pdf

9. Human and labour rights	Production of SAF should respect human and labour rights
10. Land use rights and land use	Production of SAF should respect the land rights and land use rights including indigenous and/or customary rights
11. Water use rights	Production of SAF should respect formal or customary water use rights
12. Local and social development	Production of SAF should contribute to social and economic development in regions of poverty
13. Food security	Production of SAF should promote food security in food-insecure regions

Technology Readiness Classification

Technology Readiness Levels as outlined by the U.S. Government Accountability Office:

	Technology Readiness Level (TRL)	Description
1	Basic Principles observed and reported	Scientific research begins to be translated into applied research and development.
2	Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions.
3	Analytical and experimental critical function and/or characteristic proof of concept	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology
4	Component and/or breadboard validation in a laboratory environment	Basic technological components are integrated to establish they will work better together.
5	Component and/or breadboard validation in a relevant environment	The fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment.
6	System/subsystem model or prototype demonstration in a relevant environment	The representative model or prototype system, which is well beyond that of TRL 5, is tested in its relevant environment.
7	System prototype demonstration in an operational environment	Prototype near or at the planned operations system. Represents a major step up from TRL 6 by requirement demonstration of an actual system prototype and operational environment (i.e. aircraft of the vehicle)

8	The actual system was completed and qualified through tests and demonstration	Technology has been proven to work in its final form and under expected conditions.
9	Actual system proven through successful mission operations	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational tests and evaluation.

Alastair Blanshard

Alastair.blanshard@icf.com

Alina Viehweber

Alina.viehweber@icf.com

icf.com

twitter.com/ICF

linkedin.com/company/icf-international

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