Roundtable on Sustainable Biomaterials

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Report on the Techno-Economic Assessment (TEA) of SAF Pathways

Roundtable on Sustainable Biomaterials

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The Project Advisory Group

This study has been supported by a Project Advisory Group, which guided its initiation, scoping, and conclusion. Members of the Project Advisory Group include: *ASEAN Secretariat, Association of Asia Pacific Airlines (AAPA), The Boeing Company, Civil Aviation Authority of Singapore (CAAS), DBS Bank, Singapore's Economic Development Board, GenZero, International Air Transport Association (IATA), Neste, Singapore Airlines, SkyNRG, Standard Chartered,* and *WWF Singapore.*

The findings and recommendations in this report are based on an independent analysis by the RSB and do not reflect the views of the individual Project Advisory Group members or other institutions supporting the project listed above.

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List of Abbreviations

Abbreviation	Description
ATJ	Alcohol-to-Jet
CAPEX	Capital Expenditures
CEPCI	Chemical Engineering Plant Cost Index
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CPI	Consumer Price Index
EFB	Empty Fruit Bunches
EtOH	Ethanol
FCI	Fixed Capital Investment
FT	Fischer-Tropsch
GHG	Greenhouse gas
HEFA	Hydroprocessed Esters and Fatty Acids
HRJ	Hydroprocessed Renewable Jet
HVO	Hydrogenated Vegetable Oil
IATA	International Air Transport Association
iBuOH	Isobutanol
IEA	International Energy Agency
IRR	Internal Return Rate
MARR	Minimum Acceptable Rate of Return
LEC	Landfill Emissions Credits
LHV	Low Heating Value
L&M	Labour and Maintenance Costs
LPG	Liquid Petroleum Gas
MC	Mitigation Costs
MFC	Maximum Feed Cost
MSP	Minimum Selling Price
MSW	Municipal Solid Waste
NBC	Non-Biogenic Content
NG	Natural gas
NPV	Net Present Value
OPEX	Operational Expenditures
PFAD	Palm Fatty Acid Distillate
PB	Payback
REC	Recycling Emission Credits
SAF	Sustainable Aviation Fuel
SMR	Steam Methane Reforming
TEA	Techno-economic assessment

Project outline

The project aimed to create a user-friendly TEA tool that facilitates the assessment of SAF pathways. The tool allows tailored analysis based on country- and pathway-specific data and ensures ease of use for operators and decision-makers. In consultation with the project advisory group, SAF production pathways were selected to demonstrate the tool's applicability.

Building on an existing RSB tool, the TEA tool used in this study has been significantly advanced and customised. A thorough technical review and careful adaptation of features have resulted in a tool that is precisely aligned with the study's specific needs. To determine the applicability of the TEA tool, SAF production pathways were selected in consultation with the project advisory group to conduct a tool demonstration based on secondary data. Furthermore, a new tool interface was developed to enhance the usability of the TEA tool.

Upon invitation, two validation workshops were held in July 2024 with the project advisory group and additional industry stakeholders. Subsequently, interested stakeholders had the opportunity to participate in a tool validation phase to confirm the tool's accuracy, usability, and overall effectiveness.

Figure 1 depicts the timeline of the conducted project work.

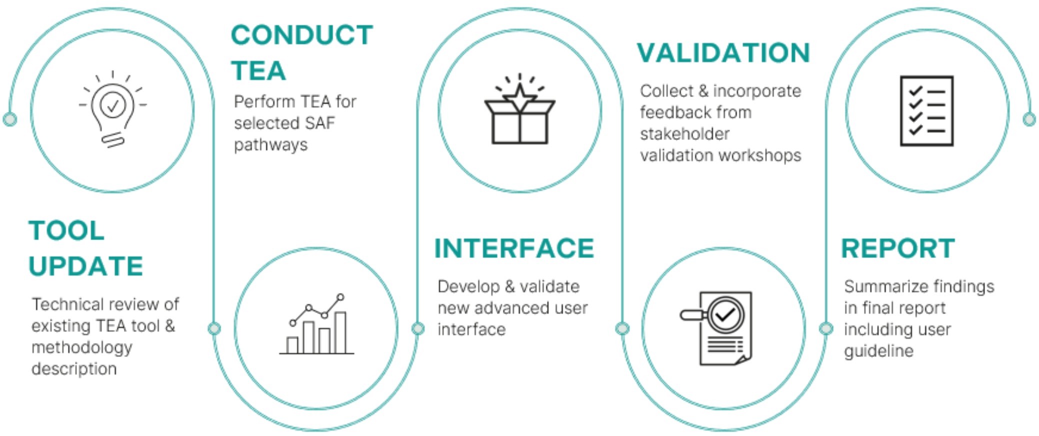

Figure 1: Timeline of work on the TEA Tool for SAF

Scope of the TEA tool

The main objective of the TEA tool is to evaluate the feasibility and cost-effectiveness of novel SAF pathways by integrating technical performance data with economic analysis and feedstock carbon intensity data. By providing insights into economic indicators such as capital and operational expenditures, the tool helps identify cost drivers and potential areas for improvement. Results obtained from the TEA can inform stakeholders, policymakers, and investors about the financial viability of SAF pathways and promote the development of promising technologies by guiding investment decisions and shaping supportive policies.

The TEA tool was developed as a Microsoft Excel® spreadsheet for straightforward user operation without the need for special software or platforms. It functions offline and supports modelling four different types of SAF production pathways within one spreadsheet:

- Hydroprocessed Esters and Fatty Acids (HEFA)
- Fischer Tropsch (FT)
- Alcohol-to-Jet (ATJ) – Stand-alone
- Alcohol-to-Jet (ATJ) – Integrated

Users can integrate country—and pathway-specific data to customise SAF pathway analyses based on primary data sources. If multiple scenarios for one pathway are to be modelled, multiple copies of the spreadsheet can be opened and used for modelling.

Default values are available for multiple reference processes per pathway to facilitate modelling. All default values presented in the tool are based on secondary data found in literature and public databases. Depending on data availability, users can rely on those default values, include their values for specific indicators, or create entirely new pathway scenario designs based on primary data. References for all default values are provided in the TEA Tool. Furthermore, all assumptions made and default values selected for the TEA tool demonstration are described in Table 2, 4 and 5.

Once a new SAF production pathway has been successfully modelled, pathway-specific results for six indicators are automatically shown in the dashboard, as described in Table 1. A more detailed description, including formulas, can be found in the appendix (Table A1).

Table 1: Description of TEA Tool Indicators

Indicator and Unit	Description & calculation formula
Net Present Value (NPV), million USD	The NPV is estimated based on the difference between the present value of costs of input flows, e.g. feedstock and electricity, and the present value of revenues generated by output flows, e.g., sales of SAF and other products, over the lifetime of the industrial plant. NPV is used in capital budgeting and investment planning to analyse a projected project's profitability. In that case, the output revenues are based on the market value of similar products. The user can select what reference prices are considered.
Minimum Selling Price (MSP), USD/m³	The MSP for SAF is determined at the facility gate, excluding taxes, where the NPV of the business case is zero. The overall costs (capital and operational) are economically allocated to SAF and the other products (such as diesel, naphtha, LPG, power surplus, etc) based on market values of similar products, such as fossil fuels. The tool compares the MSP of SAF with: i) the price of fossil kerosene (Jet A) at the producer site; and ii) a reference cost for SAF from literature or market. Both comparisons were carried out on an energy basis.

Mitigation Costs (MC), USD/tCO_{2e}	MC generally refers to the costs associated with reducing greenhouse gas (GHG) emissions through the use of SAF compared to conventional jet fuel. The MC was estimated considering the price difference between SAF and fossil kerosene (i.e., MSP and Jet A price at the producer site) and the total emission reduction. The emission reduction was estimated according to the CORSIA methodology, which compares the emission factor of fossil kerosene (89.0 gCO2e/MJ) and the emission factor of SAF on a life cycle basis.
Maximum Feed Cost (MFC), USD/t_{feed}	The MFC indicates the maximum cost for acquiring the feedstock to maintain a zero NPV. In that case, the output revenues are based on the market value of similar products. The user can select the reference prices considered. A negative value for MFC means that the feedstock would need subsidies.
Internal Return Rate (IRR), %	The Internal Return Rate (IRR) is a discount rate that makes the NPV of all cash flows equal to zero. Generally, an IRR higher than MARR (Minimum Attractive Rate of Return) indicates profitable investments.
Payback (PB); years	The PB refers to how many years are necessary for the total investment cost to be paid.

Furthermore, the TEA tool automatically performs a sensitive analysis of indicators comprising income tax rate, production scale, MARR, feedstock cost, and fossil kerosene (Jet A) price. In addition, detailed cash flow results will be automatically generated.

It is important to note that the TEA tool does not provide an in-depth environmental assessment of SAF pathways. In its scope, carbon abatement costs are calculated to determine mitigation costs, offering a preliminary understanding of potential policy impacts in this area. Accompanying environmental assessments, e.g. by applying RSB's GHG Tool, is recommended. Furthermore, the TEA tool does not consider costs associated with the transportation, blending and use of SAF, as the tool's system boundaries are from feedstock to the end of the factory gate. Other upstream costs, such as regulatory compliance and certification, and market-based mechanisms, such as book-and-claim, are not within the tool's scope.

Once a promising pathway is identified using the TEA tool, in-depth economic and environmental assessments based on full-scale process models shall be conducted before final investment decisions are made. An overview of topics not in-scope of the TEA tool are presented in Figure 2.

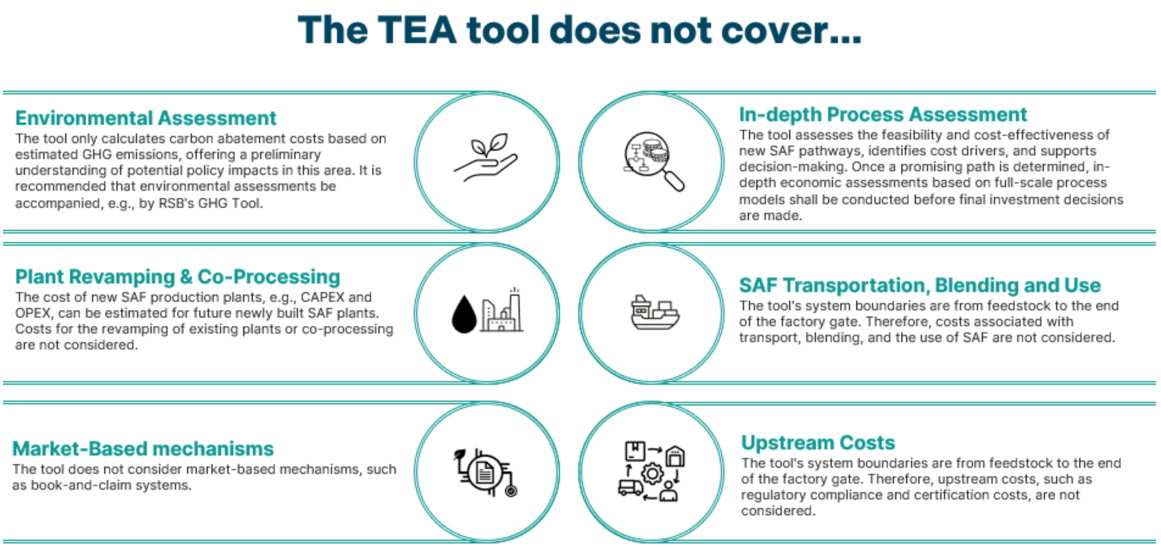

Figure 2: Topics not covered in the scope of the TEA tool.

Tool Interface

To enhance the TEA tool's usability, a new user interface consisting of three main layers was developed (Figure 3). Upon opening the Excel® spreadsheet, the user will see the Home Page, which consists of general instructions and the option to start modelling four SAF pathways. From the Home Page, the user can enter four different pathway-specific Dashboards. Each Dashboard comprises the model specifications on the left side, and the model results on the right side, which will be generated automatically once the seven steps of the model specification have been completed correctly.

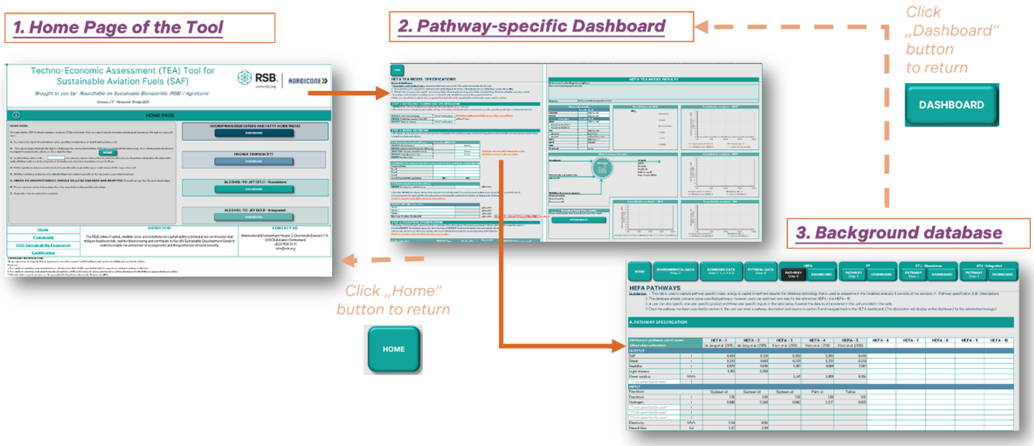

Figure 3: Overview of the three main layers of the TEA Tool for SAF: Home Page, Pathway-specific Dashboard and Background Database.

An overview of the seven modelling steps which need to be completed in the pathway-specific dashboard to maintain results is given in Figure 4. Instructions and hidden guidance notes accompany every step. Furthermore, every step is linked to the Background Database. The Background Database comprises all environmental, economic, physical, and pathway-specific data linked to the seven modelling steps. The user shall use the background database to select default values or add and select customised primary data.

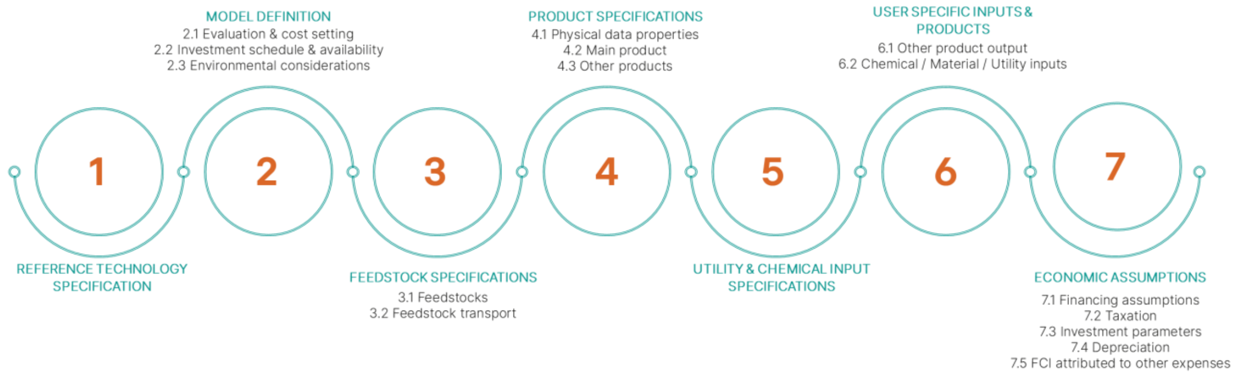

Figure 4: Overview of the seven modelling steps that users of the TEA tool must complete to receive pathway-specific results.

TEA Tool Demonstration

To demonstrate the applicability of the TEA tool, eight SAF production pathways were selected and modelled using secondary data – mainly existing literature, public databases and previous studies (Figure 5):

1. SAF from palm fatty acid distillate (PFAD) via a Hydroprocessed Esters and Fatty Acids (HEFA) process (Malaysia)
2. SAF from empty fruit bunches via a Fischer-Tropsch (FT) process (Malaysia)
3. SAF from Municipal Solid Waste (MSW) via an FT process (Malaysia)
4. SAF from sugarcane-derived ethanol (EtOH) via an Alcohol-to-Jet (ATJ) process considering a stand-alone production facility starting from EtOH (Thailand)
5. SAF from sugarcane-derived isobutanol (iBuOH) via an ATJ process considering a stand-alone production facility starting from iBuOH (Thailand)
6. SAF from sugarcane-derived EtOH via an ATJ process considering an integrated production facility starting from sugarcane (Thailand)
7. SAF from molasses-derived iBuOH via an ATJ process considering an integrated production facility starting from molasses (Thailand)
8. SAF from MSW via an FT process (Thailand)

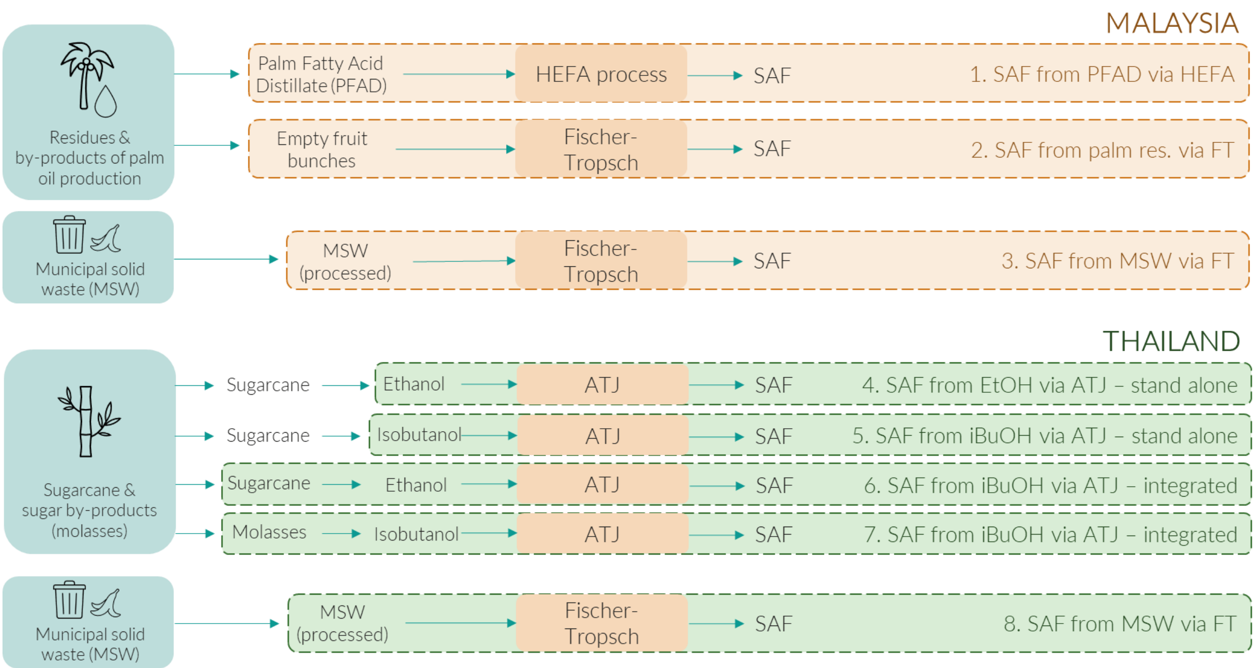

Figure 5: Overview of selected SAF pathways to demonstrate the TEA tool.

Selection of default values

Table 2 summarises all default values selected for modelling the selected SAF pathways. If only one default value is provided in the table, it means that this default value was used for modelling all eight selected SAF pathways. When modelling user-specific pathways, users shall review and, if needed, add customised values from primary sources.

Table 2: Overview and explanation of assumptions and default values for the TEA Tool modelling demonstration considering eight SAF pathways following seven modelling steps.

Step No.	Assumption	Selected default value per pathway	Explanation / Reference
1	Reference technology	*see Table 4*	The pathway that is used as a baseline to adjust and calculate the actual techno-economic results. Each pathway is specified in the pathway database for each technology with unique inputs, outputs and CAPEX specifications.
	Annual SAF production volume	1 million m³/year	The assumed amount of SAF corresponds to ~ 735.000 t per year. As a reference, Neste aims to produce 1,2 million tons of SAF in 2026 ('Neste Rotterdam, Netherlands', n.d.)
	Plant category	Nth	It represents a mature version of the technology, assuming a high TRL.
2	Evaluation year	2024	Costs are corrected according to the selected year-specific cost adjustment index.
	Industrial plant lifetime	25 years	A maximum of 35 years can be assumed.
	SAF reference price	55,12 USD/GJ (2022); 1764 USD/m³	Based on data provided by IATA (IATA Sustainability and Economics, 2023).
	Cost adjustment index	CPI – Malaysia CPI - Thailand	All economic parameters are automatically updated, considering a country-specific Consumer Price Index (*World Bank Open Data - Consumer Price Index*, n.d.). Capital costs are corrected according to the Chemical Engineering Plant Cost Index (CEPCI) (*Chemical Engineering*, n.d.)
	Location factor	1.14	CAPEX costs are adjusted by the location factor, accounting for different business costs in other geographic locations (Towler & Sinnott, 2008).
	Investment schedule (Year 0, 1, 2, 3)	HEFA: 50%, 35%, 15%, 0% ATJ-sa.: 30%, 50%, 20%, 0% ATJ-int.: 50%, 40%, 10%, 0% FT: 50%, 10%, 10%, 30%	The percentage of total capital invested for each year of construction. In the tool, 100% of the capital expenditure must be invested by year 4.
	Plant availability (Year 0, 1, 2, 3)	0%, 0%, 30%,70%	The percentage of the plant's operational capacity during construction is described (Year 0/ Year 1/Year 2/Year 3), usually starting at 0% in year 1 and gradually increasing year-over-year. In the tool, a fully operation plant must be reached by year 4.
	Carbon price, excluding taxes	0 USD/tCO_2	Price to estimate the potential revenues from carbon credits based on the CO_2 emission reductions by SAF compared with fossil kerosene.

	GHG intensities	*See Table 3*	Carbon intensity, on a life cycle basis, for SAF obtained according to the pathways selected.
3	Feedstock specifications	*See Table 5*	Reference cost assumed for each feedstock considered.
	Transportation cost	0,021 USD/t*km (2023) – Malaysia 0,033 USD/t*km (2024) – Thailand	Reference cost for feedstock transportation. Road transportation in Malaysia by truck (10 t, >150 km) (Roda, 2015) and road transportation in Thailand by truck (10 t) ('10-Wheel Truck Cargo Delivery Nationwide', n.d.) was assumed.
	Average transportation distance	300 km	An average feedstock transportation distance to the SAF plant of 300 km was assumed. A distance of 30 km from field to plant was assumed for pathway 6 (ATJ integrated from sugarcane).
4	Fossil kerosene	363 USD/t (2020); 290 USD/m³	Selected reference price for aviation fuel according to the IEA (*IEA Charts – Data & Statistics*, n.d.)
	Diesel	1052 USD/t (2024) – Thailand 835 USD/t (2024) - Malaysia	Selected reference prices for diesel in Thailand (Retail Price) (*EPPO- Thailand*, n.d.) and Malaysia (Retail Price) (ringgitplus, 2024)
	Naphtha	627 USD/t (2024)	Selected reference price for naptha (Mediterranean Naphtha, 20 May, FOB)(*ECHEMI - Naphtha Price List in Global Market*, n.d.)
	Light streams	608 USD/t (2024) – Thailand 404 USD/t (2024) - Malaysia	Selected reference price for light streams of liquid petroleum gas (LPG) in Thailand (*CEIC - Thailand Wholesale Price & VAT: LPG*, n.d.)and Malaysia (*Gas PETRONAS*, n.d.).
	Power surplus	35 USD/MWh (2020)	Selected reference price for power surplus according to Brazilian auction (*CCEE*, n.d.)
5	Hydrogen price	2380 USD/t	Selected reference price for hydrogen assuming it is obtained off-site by Steam Methane Reforming (SMR) (Zhao et al., 2015)
	Electricity	123 USD / MWh (2023) – Malaysia 90 USD / MWh (2023) - Thailand	Reference cost assumed for Malaysia according to the *Malaysian Electricity price for businesses* (*Malaysia Electricity Prices, December 2023*, n.d.); and reference cost assumed for Thailand according to *Thailand's electricity price at 69 kV and above* (Thailand Board of Investment, 2023)
	Natural gas	8,67 USD / GJ (2020) – Malaysia 8,76 USD / GJ (2022) - Thailand	Reference cost assumed for Malaysia (*Gas Malaysia*, n.d.); and reference cost assumed for Thailand (Solutions, 2023)
6	User-specific inputs	/	Non-applicable in the current modelling.
7	Financing equity	100 %	The project was assumed to be funded entirely through equity investments without debt.
	Minimum Acceptable Rate of Return (MARR)	12 %	To be considered viable, a MARR of 12% was assumed.
	Income tax rate	34 %	An income tax rate of 34% was assumed.

	Depreciation of equipment	10 years	A linear depreciation within 10 years was assumed for equipment. The value must be lower than the industrial plant lifetime considered above.
	Duration of depreciation building	10 years	A linear depreciation within 10 years was assumed for buildings. The value must be lower than the industrial plant lifetime considered above.
	Other expenses (% of FCI) (Labor, Maintenance, other taxes, overhead, other)	HEFA: 0,91%, 5,10%, 5,05%, 3,15%, 4,15% FT and ATJ: 3,50%, 10,0%, 3,0%, 1,75%, 1,60%	Other expenses were estimated based on the FCI (see Table 4). i.e., capital expenditures summed to 5% as working capital. Different assumptions were made for HEFA pathways (Cheah et al., 2017) compared to FT or ATJ pathways (Towler & Sinnott, 2008).

Table 3 summarises all default values for modelling the SAF pathways' carbon intensity as outlined by CORSIA (ICAO Environment, n.d.-a) and others.

Table 3: Overview and explanation of carbon intensity default values for the TEA Tool modelling demonstration considering eight SAF pathways.

SAF pathway	Country	Feedstock	Carbon Intensity [g CO_{2eq}/MJ]	Comment / Reference
1	Malaysia	PFAD	20,7	Global value (ICAO Environment, n.d.-a)
2	Malaysia	Palm residues (empty fruit bunches)	7,7	Agricultural residues, global value (ICAO Environment, n.d.-a)
3	Malaysia	MSW	62,9	MSW with 33,8% Non-Biogenic Content (NBC) for Malaysia (Jabatan Pengurusan Sisa Pepejal Negara, Kementerian Kesejahteraan Bandar, 2013)
4	Thailand	Sugarcane-derived Ethanol	32,6	Global value for sugarcane-derived ethanol (ICAO Environment, n.d.-a)
5	Thailand	Sugarcane-derived isobutanol	33,1	Global value for sugarcane-derived isobutanol (ICAO Environment, n.d.-a)
6	Thailand	Sugarcane (via EtOH)	32,8	Global value sugarcane (ICAO Environment, n.d.-a)
7	Thailand	Molasses (via iBuOH)	36,1	Global value molasses (ICAO Environment, n.d.-a)
8	Thailand	MSW	74,9	MSW with 40,9% NBC for Thailand (Raj & Chutima, 2018)

SAF pathway descriptions

All eight SAF production pathways selected for tool demonstration (Figure 5) were modelled based on reference processes found in the literature and are briefly described in the sections below.

SAF from HEFA processes

Hydrotreating/hydrocracking vegetable oils, animal fats or grease residues - a process called Hydroprocessed Esters and Fatty Acids (HEFA), or Hydroprocessed Renewable Jet (HRJ) or Hydrogenated Vegetable Oil (HVO) - is currently the best-known SAF process and has been tested in large-scale production of aviation biofuels. In HEFA processes, the oleaginous feedstock undergoes hydrotreatment with hydrogen in the presence of a catalyst. Unsaturated carbon bonds are saturated, and oxygen is removed. Subsequently, the hydrocarbon chains are hydrocracked in different ranges, isomerised and fractioned, producing drop-in kerosene and other products, such as diesel, naphtha, and propane. The amount of drop-in diesel and kerosene can be adjusted by operational conditions.

To demonstrate the tool's applicability, one SAF production pathway starting from palm fatty acid distillate (PFAD) applying a HEFA process was modelled (SAF pathway 1) based on a reference process from literature starting from soybean oil (HEFA-1)(de Jong et al., 2015). The reference process was designed to maximise jet fuel production. Figure 6 depicts an overview of all assumed input and output flows.

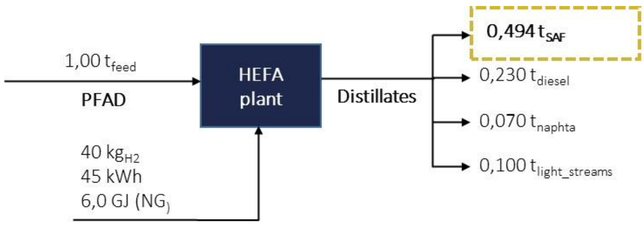

Figure 6: Overview of input and output flows assumed for modelling of SAF pathway 1 (Malaysia)

SAF from FT processes

Another thermochemical SAF production pathway is biomass gasification, followed by a syngas clean-up and the known Fischer-Tropsch (FT) process. The syngas is catalytically converted into liquid long-chain hydrocarbons, which are then cracked, isomerised and fractioned into drop-in jet fuel and other products.

To demonstrate the tool's applicability, three FT-based processes starting from Empty Fruit Bunches (EFB) (SAF Pathway 2) or Municipal Solid Waste (MSW) (SAF Pathway 3, SAF Pathway 7) were modelled based on a reference process described by ICAO (ICAO Environment, n.d.-b) (FT-3) for MSW and a conversion process for agricultural residues (de Jong et al., 2015)(FT-1) for EFB. Figure 7 depicts an overview of all assumed input and output flows for SAF pathway 2 – starting from EFB.

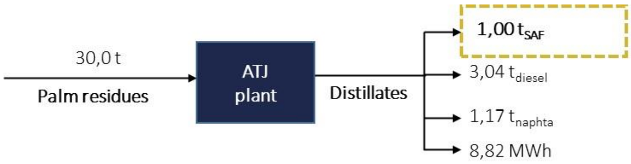

Figure 7: Overview of input and output flows assumed for modelling of SAF pathway 2 (Malaysia)

Figure 8 depicts an overview of all assumed input and output flows for SAF Pathway 3 and SAF Pathway 7 starting from MSW.

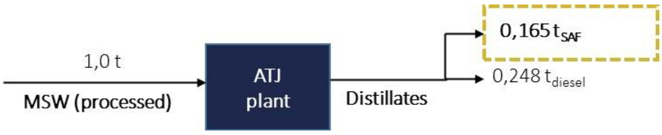

Figure 8: Overview of input and output flows assumed for modelling of SAF pathway 3 (Malaysia) and 7 (Thailand)

SAF from ATJ processes

Sugars freely available in biomass or obtained from starch or lignocellulose can be converted into drop-in kerosene using the Alcohol-to-Jet (ATJ) process with alcohols (ethanol or isobutanol) as an intermediary product. Alcohol molecules are dehydrated, oligomerised, and hydrogenated to suitable hydrocarbon chains for drop-in fuel.

Two stand-alone and two integrated SAF production pathways applying an ATJ process were modelled to demonstrate the tool's applicability. The stand-alone SAF pathway 4 starts from sugarcane-derived ethanol (EtOH) and is based on a sugarcane-ethanol conversion reference process described in the literature (ATJ-2)(Klein et al., 2018). Figure 9 depicts an overview of all assumed input and output flows.

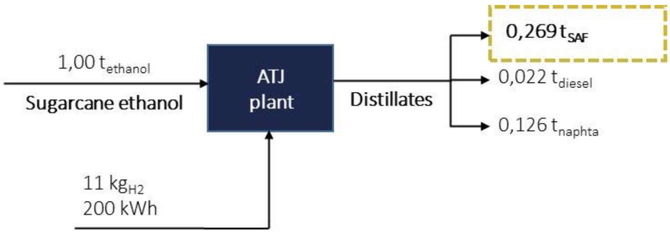

Figure 9: Overview of input and output flows assumed for modelling of SAF pathway 4 (Thailand)

The stand-alone SAF pathway 5 starts from sugarcane-derived isobutanol (iBuOH) and was based on a sugarcane-isobutanol conversion reference process described in the literature (ATJ-3)(ICAO Environment, n.d.-b). Figure 10 depicts an overview of all assumed input and output flows.

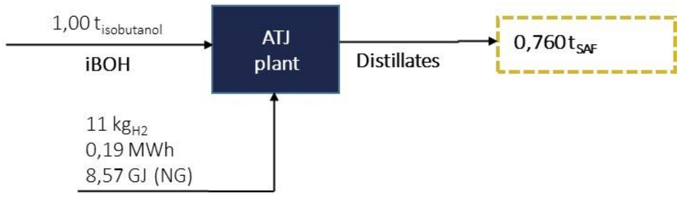

Figure 10: Overview of input and output flows assumed for modelling of SAF pathway 5 (Thailand)

The integrated SAF pathway 6 starts from sugarcane, which is converted to EtOH before being converted to SAF in an ATJ process. The first conversion step was modelled based on literature data for an optimised Brazilian sugarcane mill (Bonomi et al., 2016), while the second step was modelled based on a sugarcane-ethanol-conversion reference process described in the literature (ATJ-1, see SAF pathway 4)(Klein et al., 2018). Figure 11 depicts an overview of all assumed input and output flows.

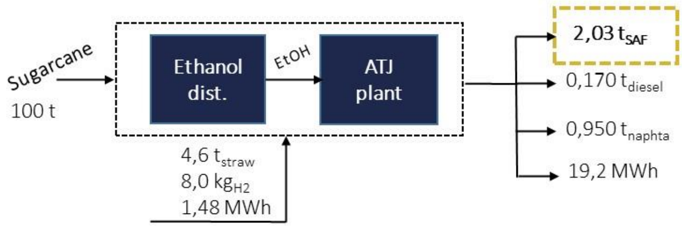

Figure 11: Overview of input and output flows assumed for modelling of SAF pathway 6 (Thailand)

The integrated SAF pathway 7 starts from molasses, which is converted to iBuOH before being converted to SAF in an ATJ process. The first conversion step was modelled based on literature data for an industrial plant for iBuOH production from molasses (Merwe van der, Abraham Blignault, 2010). In contrast, the second step was modelled based on a sugarcane-isobutanol-conversion reference process described in the literature (ATJ-3, see SAF pathway 5)(ICAO Environment, n.d.-b). An overview of all assumed input and output flows is depicted in Figure 12.

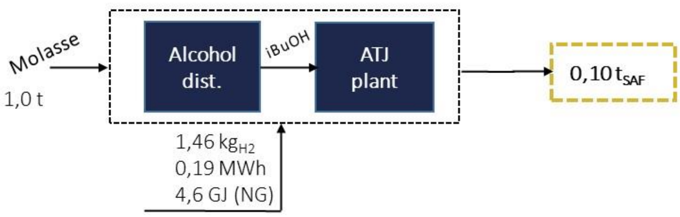

Figure 12: Overview of input and output flows assumed for modelling of SAF pathway 7 (Thailand)

Main modelling assumptions

Tables 4 and 5 show the assumptions and corresponding references for feedstock prices, feedstock-to-distillate yields, and fixed capital investment (FCI) costs.

The distillate output comprises all liquid fuels obtained during the SAF conversion process, such as diesel, naphtha, and light streams. Industrial yields for all outputs (distillate, SAF, or intermediary product) were estimated by the output and feedstock input ratio. In integrated pathways (SAF pathways 6 and 7), ethanol and isobutanol are intermediary products.

Assumptions made for capital costs were mainly based on scientific publications covering different process models. The availability of data to model pathways starting from MSW and isobutanol was limited. It was found that capital unit costs (USD/feed) are higher in FT pathways (around 1180 USD/t) and HEFA pathways (around 1000 USD/t) in comparison to ATJ pathways (200-460 USD/t).

A scaling factor of 0,6 was assumed to scale CAPEX costs towards the assumed production scale (1,0 million m³ SAF/year)(Capaz et al., 2021).

Table 4: Overview of assumed feedstock-to-distillate yields and FCI per pathway, including references.

SAF pathway	Feedstock input [Mt/year]	Distillate/ SAF output [million m³/year]	FCI [million USD]	Abbr. of reference process	Reference
1. SAF from PFAD via HEFA	0,83	1,05 (Dist.) 0,55 (SAF)	828,9	HEFA-1	(de Jong et al., 2015)
2. SAF from palm residues via FT	0,66	0,16 (Dist.) 0,02 (SAF)	594,3	FT-1	(de Jong et al., 2015)
3. SAF from MSW via FT	1,21	0,5 (Dist.) 0,2 (SAF)	1428	FT-3	(ICAO Environment, n.d.-b)
4. SAF from EtOH via ATJ	0,29	0,17 (Dist.) 0,11 (SAF)	60	ATJ-2	(Klein et al., 2018)
5. SAF from iBuOH via ATJ	0,9	1,0 (Dist.) 0,7 (SAF)	410	ATJ-3	(ICAO Environment, n.d.-b)
6. SAF from EtOH via ATJ Sugarcane – EtOH EtOH - Distillate	4,0 0,29	0,34 (EtOH) 0,17 (Dist.) 0,11 (SAF)	417,8 60	ATJ-1	(Bonomi et al., 2016), (Klein et al., 2018)
7. SAF from molasses via ATJ Molasses – iBuOH iBuOH - Distillate	1,0 0,97	0,14 (iBuOH) 0,7 (SAF)	377 410	ATJ-3	(Merwe van der, Abraham Blignault, 2010),(ICAO Environment, n.d.-b)
8. SAF from MSW via FT	1,21	0,5	1428	FT-3	(ICAO Environment, n.d.-b)

Table 5: Overview of assumed feedstock costs per pathway, including references

SAF pathway	Country	Feedstock price [USD/t]	Reference
1. SAF from PFAD via HEFA	Malaysia	730	2023 (*PFAD Palm Fatty Acid Distillate / Commodity3.Com*, n.d.)
2. SAF from palm residues via FT	Malaysia	9	2017 (Lim et al., 2022; Omar et al., 2011)
3. SAF from MSW via FT	Malaysia	16	2022 (Rangga et al., 2022)
4. SAF from EtOH via ATJ	Thailand	1229	2024 (*Thailand Ethanol Prices, 15-Jul-2024*, n.d.)
5. SAF from iBuOH via ATJ	Thailand	1250	2022 (ICAO Environment, n.d.-b)
6. SAF from EtOH via ATJ	Thailand	39	2023 (Arunmas, 2024)
7. SAF from molasses via ATJ	Thailand	200	2024 (*Thailand Sugarcane Molasses*, n.d.)
8. SAF from MSW via FT	Thailand	5	2016 (Abbasi et al., 2020)

Modelling results

To demonstrate the TEA Tool's applicability, economic indicators (Table 1) were calculated for eight selected SAF pathways (Figure 5) based on default values and pathway-specific assumptions (Table 2 – Table 5) found in the literature.

Minimum Selling Price (MSP)

Results obtained for the MSP of the eight selected SAF pathways, a fossil kerosene and two SAF market reference prices are depicted in Figure 13.

The MSP was estimated such that production costs were allocated to the amount of SAF produced, considering its share of the revenues. In all scenarios, the MSP of SAF (388 – 3087 USD/m^3) was higher than that of fossil kerosene (362 USD/m^3). In energy terms, the SAF price (at the gate, without taxes) was estimated to be 38% to 10-fold higher than that of fossil kerosene. 5 of 8 pathways had a lower or equal MSP than the SAF reference price. FT-based pathways (for MSW or palm residues) presented the lower MSP, while alcohol-based pathways (stand-alone or integrated) presented the higher ones.

Figure 13: Minimum Selling Prices (MSP) were determined for eight selected SAF pathways by applying the TEA Tool for SAF.

Net Present Value (NPV)

Results obtained for the NPV of the eight selected SAF pathways are depicted in Figure 14. The NPV was estimated, assuming that distillates and power surplus would be sold at the current market prices of similar products. In all scenarios, a negative NPV was estimated since the current market prices for the outputs (e.g. distillates, and power surplus) do not cover the total production costs. More accurate NPV values can be obtained when using primary input data, while a positive NPV could be reached by leveraging technical, economic, and political measures.

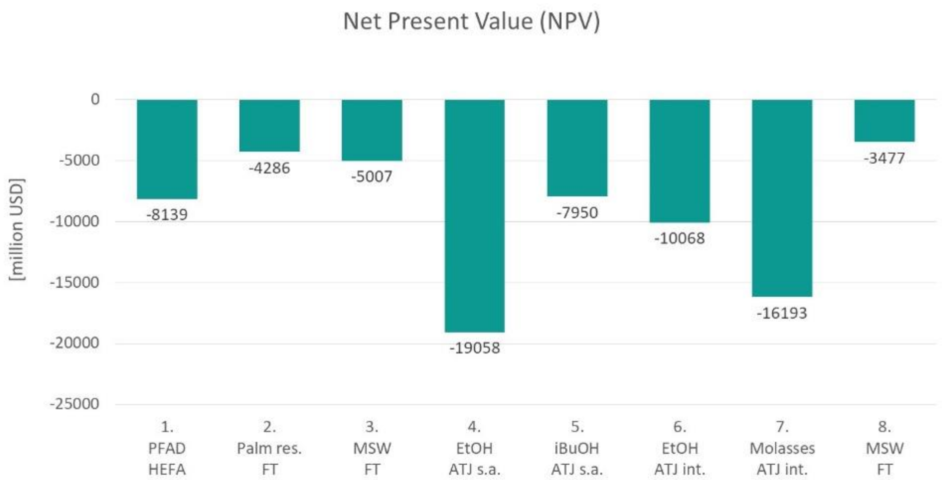

Figure 14: Net Present Values (NPV) were determined for eight selected SAF pathways by applying the TEA Tool for SAF.

Breakdown of MSP

Results obtained for the breakdown of MSP of the eight selected SAF pathways are depicted in Figure 15. Capital costs (CAPEX) accounted for around 35% of production costs in FT-based paths. On the other hand, feedstock costs are relevant for HEFA and, mostly, for ATJ-based pathways, accounting for more than 50% of the total costs. In SAF pathway 4, the ethanol input can reach almost 90% of the total costs, followed by SAF pathway 5, where isobutanol corresponds to around 75% of them. Finally, input costs account for around 20% of molasses-based SAF pathways (pathway 7), mostly due to the high demand for natural gas (46 GJ/t_{SAF}).

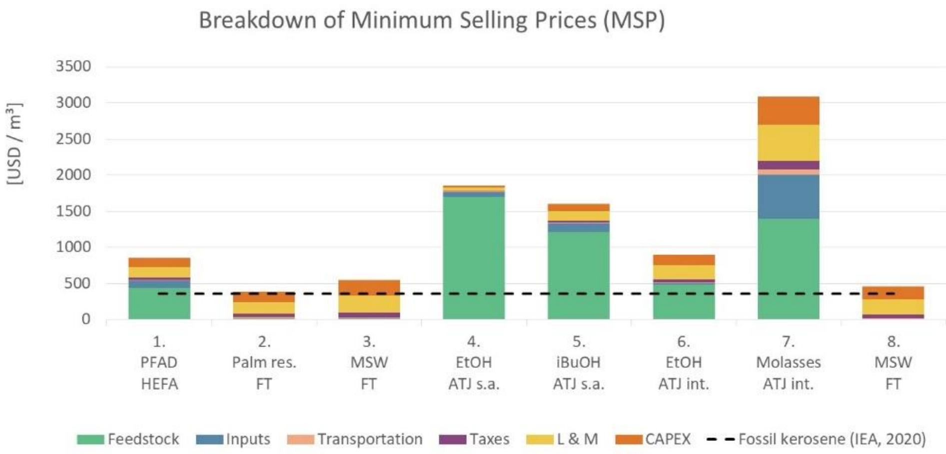

Figure 15: The breakdown of MSP was determined for eight selected SAF pathways by applying the TEA Tool for SAF.

Mitigation Costs (MC)

Results obtained for MC of the eight selected SAF pathways are depicted in Figure 16. The MC quantifies the costs associated with reducing greenhouse gas (GHG) emissions through the use of SAF compared to conventional jet fuel. The mitigation costs for 5 out of 8 pathways will be lower than 500 USD/tCO_2e avoided. The lowest MC was found for the palm residues-based FT pathway (50 USD/tCO_2e avoided) due to the low difference between MSP and fossil kerosene price (see Figure 13) and high avoided carbon emissions (see the lowest carbon intensity in Table 3). Alcohol-based pathways resulted in higher MC. The MC of MSW-based pathways (around 390 - 460 USD/tCO_2e avoided), are close to MC obtained for ethanol-based pathways (SAF pathway 6) due to a high carbon intensity (60-75 gCO_{2e}/MJ) related to the non-biogenic carbon (NBC) assumed for each feedstock.

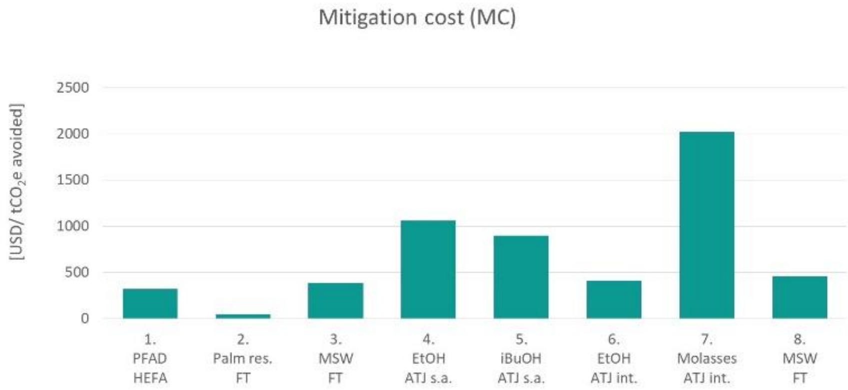

Figure 16: MC determined for eight selected SAF pathways applying the TEA Tool for SAF.

Maximum Feed Cost (MFC)

Figure 17 depicts the MFC results obtained for the eight selected SAF pathways and the assumed feedstock prices. The MFC indicates the feedstock cost to achieve a zero NPV. In general, negative MFC implies that feedstock subsidies would be needed for the SAF producer, which might be particularly interesting in the context of MSW or residue management. MFC could be positive in pathways where the feedstock contributes substantially to production costs (see SAF pathway 4).

Figure 17: MFC were determined for eight selected SAF pathways by applying the TEA Tool for SAF.

Avoided Emissions

Results obtained for avoided emissions are depicted in Figure 18. Assuming the production of 1 million m³ of SAF per year, avoided carbon emissions of more than 1,0 million tCO_{2e} per year could be achieved, considering SAF is replacing fossil kerosene. These results are directly influenced by the carbon intensity (gCO_{2e}/MJ) assumed for each pathway (see Table 3). Agricultural residues have the lowest carbon intensity, which leads to the highest amount of carbon emission avoided. Even as residue, MSW is influenced by the assumed non-biogenic carbon (NBC) content, which differs between Malaysia and Thailand. However, according to the CORSIA methodology, it is possible to account for carbon emission credits such as Landfill Emissions Credit (LEC) or

Recycling Emissions Credit (REC), which would decrease the carbon intensity of MSW-based pathways (see section 6 in (International Civil Aviation Organization (ICAO), 2024).

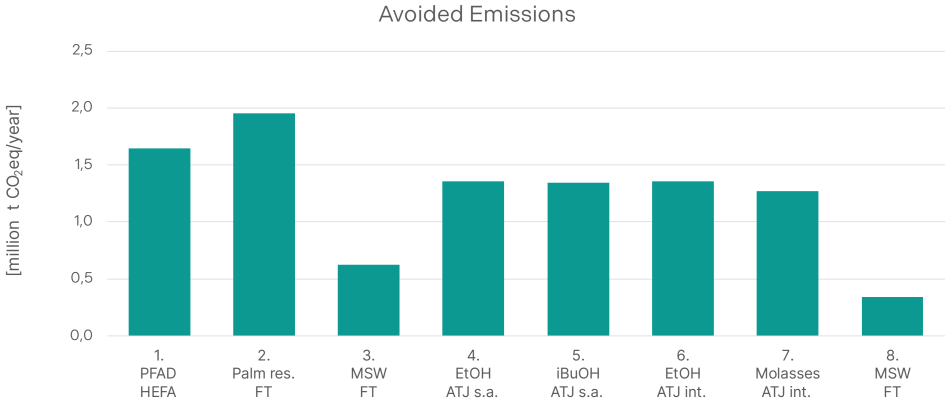

Figure 18: Avoided emissions were determined for eight selected SAF pathways by applying the TEA Tool for SAF.

Stakeholder Tool Validation

Validation Workshops

Upon invitation, two validation workshops were held in July 2024 with the project advisory group and additional industry stakeholders, with almost 50 attendees in total. In both workshops, participants engaged actively in discussions, addressing multiple questions regarding the tool's usability, functionality, and potential impact.

Most participants had no or only limited previous experience with TEA for SAF (see Figure 19, left). Around 40% of the participants indicated that they would be interested in using the tool to model multiple SAF pathways with primary data, meaning that internally available country-specific data could be used to conduct the assessment (see Figure 19, right). Another 30% indicated that they would use secondary data for modelling, indicating that no primary data might be available.

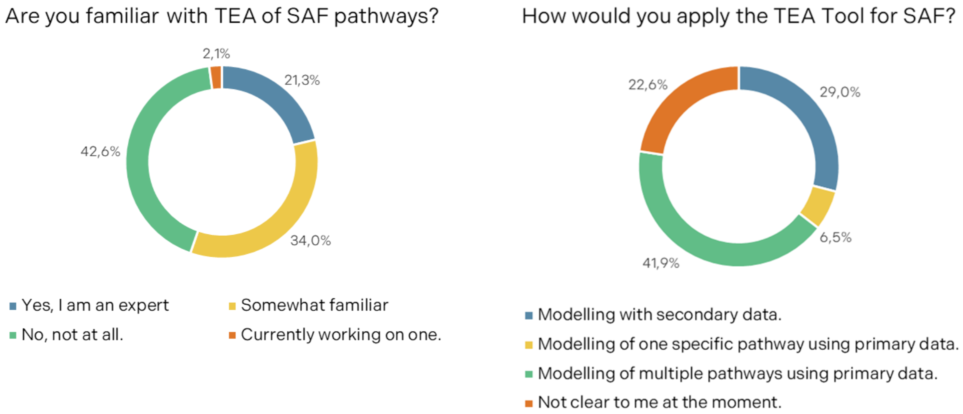

Figure 19: Feedback obtained during stakeholder validation workshops.

Furthermore, stakeholders provided general feedback that the tool's goal and scope were clear to them and that its structure was easily understandable.

From a stakeholder perspective, the TEA tool for SAF can provide the following benefits:

- Ability to evaluate commercial viability and likelihood of success of various SAF production processes
- Standardised TEA for SAF
- Identification of investment focus areas
- Identification of economic hot-spots
- Assess the impact of different feedstocks
- Assess the impact of different regions
- Support the decision-making of stakeholders in different countries by providing more information that current SAF price monitors

- Identification of potential future policies to promote SAF
- Identification of the level of subsidies for SAF
- Calculation of avoided emissions

In future tool versions, the following features would be beneficial according to stakeholders:

- Assessment of environmental impacts / Life Cycle Assessment results
- Recommendations for SAF premium prices
- Provision of data to register on the positive list
- Include upstream costs, such as SAF transportation, blending and certification
- Expand the tool's scope to other regions

Tool Validation Phase

Interested stakeholders had the opportunity to participate in a tool validation phase to confirm the tool's accuracy, usability, and overall effectiveness. To this end, the latest tool version was shared with user guidelines and video tutorials. Stakeholders provided feedback by e-mail and by answering a short online survey.

In general, tool users found the tool easy to use, with clear and easy-to-understand instructions and prompts. Stakeholders stated that the tool provided them with relevant high-level results that were useful for further detailed analysis and decision-making. Most users found that the tool can be used easily for modelling with some preliminary TEA knowledge. Others found it more challenging to select data suitable for their country-specific pathway.

The tool's layout and design were ranked with an average of eight out of ten points. The only suggestion for visual improvement concerned the current visualisation of the performed sensitivity analysis. As a result, a line-based visualisation was replaced by a tornado plot visualisation to make it easier for users to understand the sensitivity of different input parameters. Furthermore, additional guidance was incorporated into certain sections.

On average, the overall experience of the TEA tool for SAF was ranked with nine out of a maximum of ten points.

In future tool versions, the following features would be beneficial according to stakeholders:

- Inclusion of an availability factor of the SAF plant, e.g. taking different plant operation times into account depending on seasonal and regional feedstock availability.
- More guidance and examples, e.g. step 7.5 (FCI attributed to other expenses).
- Inclusion of more pathways, such as Power-to-X/ e-SAF.
- More detailed modelling of feedstock processes (e.g. seed-to-oil conversion steps).
- Include more environmental parameters in the assessment to cover relevant environmental impacts.
- Include background data of more regions, e.g. in Africa.
- Include an option to select custom sensitivity ranges for the sensitivity analysis.
- Tailor tool to specific groups of users, e.g. technical experts vs. non-technical experts.

Conclusions

Economic parameters play a critical role in SAF financing by assessing the cost competitiveness and potential return on investment for different SAF production pathways. To facilitate techno-economic assessments at an early stage, an Excel®-based TEA tool for SAF pathways was developed. The tool allows determining relevant economic indicators for four types of production pathways by completing seven modelling steps. The TEA tool's applicability for SAF was demonstrated by modelling multiple SAF production pathways. Furthermore, feedback from multiple stakeholder validations was incorporated to ensure user-friendliness and relevance for real-life decision-making.

Taken together, the TEA tool demonstration and stakeholder validations highlighted that the TEA tool can be used to:

- Identify promising SAF routes at an early stage of process development;
- Determine key cost contributors for different production pathways;
- Pinpoint the impact of individual measures that could be taken to render SAF production profitable, e.g. subsidies for feedstock prices, mitigation costs, etc.

Consequently, the TEA tool can help decision-makers identify promising country- and feedstock-specific SAF pathways and leverage technical, economic, or political measures to drive pathway development and ensure future pathway profitability.

The high interest of stakeholders from Southeast Asia and beyond in participating in the validation workshops and the tool validation phase highlights the demand for and relevance of techno-economic assessments for novel SAF production pathways. The consistently high rankings received across all survey questions during the workshops and the tool validation phase demonstrate the tool's potential to drive meaningful improvements in deploying novel SAF production pathways.

Lastly, stakeholders have expressed a strong interest in seeing future versions of the tool include additional features, such as environmental assessments, more country-specific background data, SAF upstream costs, and additional pathways, to enhance its value.

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Appendix

Table A 1: Detailed description of TEA Tool Indicators, including formulas.

<table>
<tr><th>Indicator and Unit</th><th>Description & calculation formula</th></tr>
<tr><td>Net Present Value (NPV), million USD</td><td>The NPV is estimated based on the difference between the present value of costs of input flows, e.g. feedstock and electricity, and the present value of revenues generated by output flows, e.g., sales of SAF and other products, over the lifetime of the industrial plant. NPV is used in capital budgeting and investment planning to analyse a projected project's profitability. In that case, the output revenues are based on the market value of similar products. The user can select what reference prices are considered.

Formula:
$$NPV = \sum_{n=1}^{N} \frac{C_n}{(1 + IRR)^n}$$
N: lifetime of the industrial plant [years]
n: time period [years]
C_n: net cash flow at the time period [million USD], which is determined by subtracting all cash inflows (sum of capital costs, income tax, operational costs, transportation costs, labour and maintenance costs) from all cash outflows (sum of revenues generated from products).
IRR: Internal Return Rate [%], assumed at the Minimum Attractive Rate of Return (MARR)</td></tr>
<tr><td>Minimum Selling Price (MSP), USD/m³</td><td>The MSP for SAF is determined at the facility gate, excluding taxes, where the NPV of the business case is zero. The overall costs (capital and operational) are economically allocated to SAF and the other products (such as diesel, naphtha, LPG, power surplus, etc) based on market values of similar products, such as fossil fuels.

The tool compares the MSP of SAF with: i) the price of fossil kerosene (Jet A) at the producer site; and ii) a reference cost for SAF from literature or market. Both comparisons were carried out on an energy basis.</td></tr>
<tr><td>Mitigation Costs (MC), USD/tCO_{2e}</td><td>MC generally refers to the costs associated with reducing greenhouse gas (GHG) emissions through the use of SAF compared to conventional jet fuel. The MC was estimated considering the price difference between SAF and fossil kerosene (i.e., MSP and Jet A price at the producer site) and the total emission reduction. The emission reduction was estimated according to the CORSIA methodology, which compares the emission factor of fossil kerosene (89.0 gCO2e/MJ) and the emission factor of SAF on a life cycle basis.

Formula:
$$MC = \frac{P_{Jet\ A} - MSP_{SAF}}{ER}$$
$P_{Jet\ A}$: Fossil kerosene price at producer site [USD/GJ]
MSP_{SAF}: Minimum Selling Price of SAF, see above [USD/GJ]
ER: Emission reduction [$kgCO_{2e}/GJ$]
$$ER = 3.16\ x\ 23.0\ x\ \left(1 - \frac{EF}{89.0}\right)$$
EF: Carbon footprint of SAF, on life cycle basis [gCO_{2e}/MJ]

The MSP can be translated into USD/m³, taking the assumed Low Heating Value (LHV) of the fuel into account.</td></tr>
</table>

	The annual avoided emissions (million tCO_2e) are also estimated based on the industrial plant's scale of production and the carbon abatement provided by SAF.
Maximum Feed Cost (MFC), USD/t_{feed}	The MFC indicates the maximum cost for acquiring the feedstock to maintain a zero NPV. In that case, the output revenues are based on the market value of similar products. The user can select the reference prices considered. A negative value for MFC means that the feedstock would need subsidies.
Internal Return Rate (IRR), %	The Internal Return Rate (IRR) is a discount rate that makes the NPV equals zero. Generally, an IRR higher than MARR (Minimum Attractive Rate of Return) indicates profitable investments. Formula: $$0 = NPV = \sum_{n=1}^{N} \frac{C_n}{(1+IRR)^n}$$ N: lifetime of the industrial plant [years] n: period [year] C_n: net cash flow at the time period [million USD], which is determined by subtracting all cash inflows (sum of capital costs, income tax, operational costs, transportation costs, labour and maintenance costs) from all cash outflows (sum of revenues generated from products). IRR: Internal Return Rate [%]
Payback (PB); years	The PB refers to how many years are necessary for the total investment cost to be paid. Formula: $$Payback\ period = \frac{Cost\ of\ Investment}{Average\ Annual\ Cash\ flow}$$