Spatially explicit assessment of the feasibility of sustainable aviation fuels production in Brazil: results of three case studies

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1. Maps of estimated costs of production of feedstocks

Figure 3 (in the paper) illustrates the results of estimated sugarcane production costs in a five-year cycle. Similar maps, for soybean, eucalyptus and corn, are presented in Figure SM1. The estimates indicate costs in new production areas, supposing cropping will occur displacing pasturelands (in 2018). Land prices (for pasturelands) in 2018 were considered as opportunity costs.

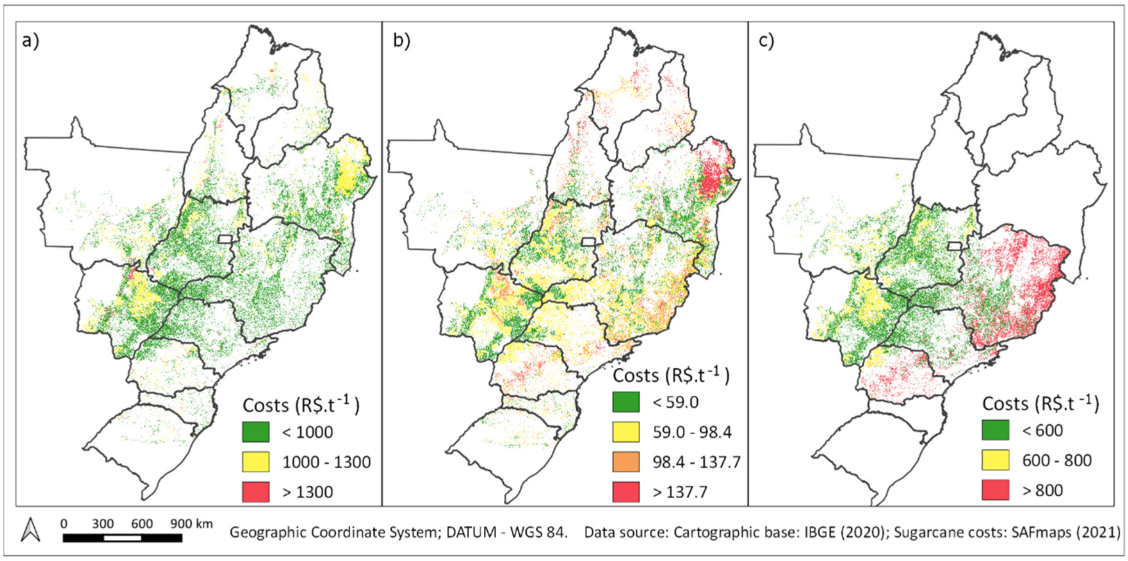

Figure S1. Estimated production costs for soybean (a), eucalyptus (b) and corn (c) in the areas assessed.

2. About transportation costs

The cost of transporting wood (in $R\$.t^{-1}.km^{-1}$) (2018) is calculated by equation (1), which was adjusted for different estimates presented by [1]. The values obtained with this function are equivalent to those presented by [2], in $R\$.m^{-3}.km^{-1}$, for distances between 100 and 140 km, using trucks with a transport capacity of 54 t.

The values obtained by equation (1) were compared with the transport costs for different loads, for specific cases, and proved to be adequate. Thus, the function was used for different feedstocks.

$$K = 1.3322 \, . \, D^{-0.3076} \quad (1)$$

Where K is the cost (BRL.t^{-1}.km^{-1}) and D is the distance (km).

Vassalo [2] states that the transport of liquids by pipeline is 4.5 to 5.7 times cheaper (in \$.t^{-1}.km^{-1}) than the transport by trucks. Here it was used 5.1 for estimating the costs due to the use of pipelines.

From the literature review [3-5], it was observed that the cost ratio of rail/road freight, expressed in \$.t^{-1}.km^{-1}, varies between 0.31 and 0.74 for distances greater than 1,000 km, with a clearer indication that 0.50 could be used for a preliminary assessment. Here, 0.50 was used.

3. Hypotheses used for estimating MSP of SAF production

The two main sources for the investments and technical parameters of the SAF industrial units are [6-7]. In all cases it was assumed an annual capacity factor 90%.

3.1 FT-SPK

Based on [6], in the reference case the estimated total investment cost (TIC) would be 599.01 million EUR (2018). The TIC was updated from what is shown in the reference [6] using the Chemical Engineering Price Index [8]. The capacity of SAF production of this plant is 61.2 t.day^{-1}. For estimating the TIC in case of 2 to 4 modules, scale exponent assumed was 0.9. The annual operation and maintenances costs were estimated at 11.65% of the TIC.

Table SM1 summarizes parameters considered in the FT-SPK case. Table SM2 presents the factors used to calculate the production of co-products in the FT-SPK unit, and Table SM3 presents prices for inputs and co-products (prices used in the allocation process between the FT products).

Table S1. Parameters assumed in the FT-SPK case.

Parameter	Value	Unit
Output/Input (mass basis)	0.17	t.t^{-1} (FT liquids/dry wood)
SAF/FT liquids (mass basis)	0.15	t.t^{-1} (SAF/FT liquids)
Wood after harvesting – humidity index	104	%
Wood after harvesting – density	0.985	t.m^{-3}
Wood at the industry – density	0.774	t.m^{-3}

Table S2. Co-products in the FT-SPK route.

Co-product	Factor	Unit
Diesel oil	0.657	t.t^{-1} (diesel/ FT liquids)
Naphtha	0.193	t.t^{-1} (naphtha/ FT liquids)
Surplus electricity	0.015	MWh.GJ^{-1} of input

Table S3. Prices of energy carriers.

Product or co-product	Price
Jet-fuel (SAF)	480 ($EUR.t^{-1}$)
Diesel oil	446 ($EUR.t^{-1}$)
Naphtha	363 ($EUR.t^{-1}$)
Surplus electricity (sold to the grid)	30 ($EUR.MWh^{-1}$)

3. HEFA-SPK

Based on [6], in the reference case the estimated total cost investment (TIC) would be 668.25 million EUR (2018), after corrections based on [8]. The SAF production capacity of this plant is 245.1 $t.day^{-1}$. For exploring scale effects, the scale exponent assumed was 0.6. The annual operation and maintenances costs were estimated at 5.70% of the TIC, plus the costs related to natural gas, hydrogen and electricity.

Table SM4 presents the factors used to calculate the production of SAF and co-products in the HEFA-SPK unit, while Table SM5 presents prices for inputs and co-products (prices used in the allocation process between product and co-products).

Table S4. Co-products in the FT-SPK route.

SAF & co-products	Factor	Unit
SAF	0.145	$t.t^{-1}$ (SAF/hydrocarbons)
Diesel oil	0.769	$t.t^{-1}$ (diesel/hydrocarbons)
Naphtha	0.020	$t.t^{-1}$ (naphtha/hydrocarbons)
Propane	0.047	$t.t^{-1}$ (propane/hydrocarbons)
LPG	0.018	$t.t^{-1}$ (LPG/hydrocarbons)

Table S5. Assumed prices of product and co-products.

Product & co-products	Price
Jet-fuel (SAF)	480 ($EUR.t^{-1}$)
Diesel oil	446 ($EUR.t^{-1}$)
Naphtha	363 ($EUR.t^{-1}$)
Propane	288 ($EUR.t^{-1}$)
LPG	288 ($EUR.t^{-1}$)

Table 6 presents information about the costs of required utilities, per tonne of feedstock.

Table S6. Assumed prices of the required inputs.

Utilities	Requirement	Unit	Price
Natural gas	150	m^3/t^{-1} of soy oil	0.3 $EUR.m^{-3}$
Hydrogen	27	kg/t^{-1} of soy oil	854 $EUR.t^{-1}$
Electricity	88	kWh/t^{-1} of soy oil	70 $EUR.MWh^{-1}$

3.3 ATJ-SPK

Based on [6], in the reference case the estimated total cost investment (TIC) would be 69.41 million EUR (2018), after corrections based on [8]. The SAF production capacity of this plant is 245.1 $t.day^{-1}$. The annual operation and maintenances costs were estimated at 7.20% of the TIC, plus the costs related to natural gas, hydrogen and electricity.

Table SM7 presents the factors used to calculate the production of co-products in the ATJ-SPK unit, Table SM8 presents prices for inputs and co-products (prices used in the allocation process between product and co-products), while Table 9 presents information about the costs of required utilities, per tonne of feedstock.

Table S7. Co-products in the FT-SPK route.

SAF & co-products	Factor	Unit
SAF	0.751	t.t^{-1} (SAF/hydrocarbons)
Diesel oil	0.088	t.t^{-1} (diesel/hydrocarbons)
Naphtha	0.161	t.t^{-1} (naphtha/hydrocarbons)

Table S8. Assumed prices of product and co-products.

Product & co-products	Price
Jet-fuel (SAF)	480 (EUR.t^{-1})
Diesel oil	446 (EUR.t^{-1})
Naphtha	363 (EUR.t^{-1})

Table S9. Assumed prices of the required inputs.

Utilities	Requirement	Unit	Price
Hydrogen	8	kg/t^{-1} of ethanol	854 EUR.t^{-1}
Electricity	220	kWh/t^{-1} of ethanol	70 EUR.MWh^{-1}

3.4 Economic and financial assumptions

Table SM10 presents assumptions used in constructing the cash flow to calculate the MSP of SAF.

Table S10. Assumptions for calculating the MSP of SAF.

Parameter	Value	Unit
Plant lifetime	25	Year
Depreciation period (straight linear method)	10	Year
Debt-to-equity ratio	80:20	%
Interest rate on debt (per year)	8	%
Rate of principal payments	15	Year
Discount rate (per year)	10	%
Corporate tax rate (over net annual outcome)	22	%
Parameters during construction period	**TIC schedule**	**Plant availability**
Year -2	30%	0%
Year -1	50%	0%
Year 0	20%	30%
Year 1		70%
Year 2		100%

4. Assumptions related to ethanol production

The costs of producing ethanol in a flex mill (i.e. producing from sugar cane and corn, being this the complementary feedstock) are based on [9]. Among the configurations presented in the reference, the one that corresponds to the parameters shown in Table SM11 was chosen. This is not the configuration that leads to lower ethanol costs, but the cost difference is not as pronounced (about 5%).

OPEX was estimated assuming fixed and variable components: 2.5% and 4% of the investment due to each feedstock, per year, and 10.1 and 36.3 R$.t^{-1}, respectively, for sugarcane and corn. Scaling was estimated considering that the exponent factor is 0.60.

In estimating ethanol production costs it was assumed that surplus electricity would be sold by 150 BRL.MWh^{-1}, and DDG would be sold by 500 BRL.t^{-1}.

Table S11. Reference parameters used to estimate ethanol production costs from sugarcane and corn (as a complementary feedstock).

Parameter	Value	Unit
Input as sugarcane	3,000	$kt.y^{-1}$
Input as corn	394.14	$kt.y^{-1}$
Anhydrous index production	85.5	$L.t^{-1}$ of sugarcane
Anhydrous index production	379.6	$L.t^{-1}$ of corn
DDG production	280	$kg.t^{-1}$ of corn
Surplus electricity	56.7	$kWh.t^{-1}$ of sugarcane
Days processing sugarcane	200	$days.y^{-1}$
Days processing corn	120	$days.y^{-1}$

5. Heat Content

The assumed heat content of different feedstocks/fuels is presented in the table SM12.

Table S12. Assumed heat content of different fuels.

Feedstock/Fuel	LHV ($MJ.kg^{-1}$)	Comment	Reference
Wood (dry)	18.07		[10]
Wood (wet)	11,29	With 60% moisture; to be transported	[10]
Soy oil	35.96		[11]
Anhydrous ethanol	28.24		[12]
Jet-fuel (SAF)	42.80		[12]

6. Estimating Emission Reductions

According to ICAO CORSIA [13], emission reductions (ER) due to the use of SAF, in tonnes of CO_2, should be estimated by equation (2):

$$ER = FCF\ x\ \left[MS\ x\ \left(1 - \frac{LS}{LC}\right)\right] \quad (2)$$

Where ER is the estimated emission reductions (t_{CO2}), FCF is the Fuel Conversion Factor (3.16 in case of displacing Jet-fuel A), MS the mass of SAF used (here assumed 1 t of SAF), LS the estimated life-cycle emission value of SAF (67.4 $gCO_2e.MJ^{-1}$ for HEFA-SPK from soy, produced in Brazil, and 32.8 $gCO_2e.MJ^{-1}$ for ATJ-SPK from sugarcane ethanol, also produced in Brazil), and LC the baseline life-cycle emissions of fossil fuel (89 $gCO_2e.MJ^{-1}$).

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