SUPPLEMENTARY MATERIALS (SM)

- **SM 1 - SPE Base Oils**

High Performance, Environmentally Acceptable, and Sustainable
Biobased · Biodegradable · Non-Toxic · Non-bioaccumulating

Typical Physical Properties by Viscosity Grade		32S	46S	46U	68S	68U	100S
Kinematic Viscosity (KV) *40°C (cSt)*	ASTM D445	29.5	44.2	47.8	69.4	67.0	96.9
Kinematic Viscosity (KV) *100°C (cSt)*		6.1	8.6	10.7	12.1	13.0	15.5
Viscosity Index	ASTM D2270	162	177	196	173	198	170
Biodegradation *(%)*	OECD 301B	>80	>80	>80	>80	>80	>80
Biobased Carbon *(%)**	ASTM D6866	62.5	50.0	76.0	59.0	65.5	65.5
HX-1 Incidental Food Contact	—	✓	✓	✓	✓	✓	✓
Pour Point *(°C)*	ASTM D97	-60	-42	-30	-33	-39	-36
Digital Density *40°C (g/cm³)*	ASTM D4052	0.97	0.96	0.97	0.95	0.95	0.93
Flash Point, COC *(°C)*	ASTM D92A	236	235	300	248	296	262
Fire Point, COC *(°C)*	ASTM D92A	262	264	324	276	322	280
Aniline Point *(°C)*	ASTM D611	< -10	< -10	< -10	< -10	< -10	< -10
Noack Volatility *Weight Loss (%)*	ASTM 5800A	14.2	13.35	0.8	6.73	1.0	4.51
Copper Corrosion *3hrs., 100°C*	ASTM D130	1A	1B	1A	1B	1B	1B
Sonic Shear Stability *KV Change (%)*	ASTM D5621	-0.34	-0.86	0.43	-0.58	-0.21	-0.4
Four Ball Wear *Scar Diameter (mm)*	ASTM D4172	0.50	0.48	0.63	0.53	0.59	0.54
Demulsibility *(ml)*	ASTM D1401	40-40-0	40-40-0	40-40-0	40-40-0	40-40-0	40-40-0
Time (min. to 0 emulsion)		5	20	25	25	5	5
Thermal Stability	ASTM D2070						
Cu Appearance		1	1	1	1	1	1
Steel Appearance		1	2	1	2	2	1
Total Sludge (mg/100ml)		4.6	4.0	1.9	6.1	0.85	1.7
Hydrolytic Stability	ASTM D2619						
Copper Loss (mg/cm²)		-0.08	-0.01	-0.05	-0.03	-0.06	-0.03
Cu Appearance		Shiny, 1B	Shiny, 1B	Shiny, 1B	Shiny, 1B	Shiny, 1B	Shiny, 1B
KV Change (%)		-3.27	-2.14	-0.39	-0.16	-2.41	-1.79
Change in AN (mg KOH/g)		0.28	0.13	0.44	0.20	0.86	0.46
Insolubles (%)		0.02	0.02	0.03	0.03	0.04	0.02
Scanning Brookfield Technique	ASTM D5133						
Temp. (°C) @ Vis. 5000 cP		-33.4	-26.7	-23.2	-23.1	-24.4	-17.6
Temp. (°C) @ Vis. 10000 cP		-37.8	-32.0	-25.1	-28.8	-29.8	-23.3
Temp. (°C) @ Vis. 20000 cP		-42.0	-36.7	-28.1	-33.8	-33.3	-28.5
Temp. (°C) @ Vis. 30000 cP		—	-39.3	-30.4	-36.5	-35.3	-31.0
Temp. (°C) @ Vis. 40000 cP		—	-41.0	-32.3	-38.4	-36.7	-31.9
Gelation Temp. (°C)		-26.3	—	-23.7	—	—	-32.3
Gelation Index		7.1	<6	14.9	<6	<6	8.2

* Calculated values for 32S, 46U, 68S, 100S

Figure 1: Performance features of saturated SPE base oils supplied by the industry manufacturers.

- **SM 2 – Life Cycle Inventory Data**

Table 1: Life cycle Inventory of the SPE manufacturing. Note: VG represents the industrial company's proprietary data based on different viscosity grades (VG) and could be made available based on reasonable requests. Different grades of the SPE use different combinations of fatty acids.

Inputs	**Amount (kg)**	**Source - Ecoinvent 3.10 Database**
Raw Materials		
Proprietary polyol	VG	Modeled based on industrial manufacturers primary data
Fatty Acid	VG	fatty acid production, from coconut oil | fatty acid | Cutoff, S
	VG	fatty acid production, from palm oil | fatty acid | Cutoff, S
	VG	tall oil refinery operation | fatty acid | Cutoff, S
Octanoic Acid	VG	fatty acid production, from coconut oil | fatty acid | Cutoff, S
Methane Sulfonic Acid	VG	methane sulfonic acid production | methane sulfonic acid | Cutoff, S
Caustic Soda/Sodium Hydroxide	VG	chlor-alkali electrolysis, diaphragm cell | sodium hydroxide, without water, in 50% solution state | Cutoff, S
Soda Ash/Sodium Carbonate	VG	market for soda ash, dense | soda ash, dense | Cutoff, S
	Amount (tons-km)	
Raw Materials Transport	>32	market for transport, freight, lorry >32 metric ton, EURO1 | transport, freight, lorry >32 metric ton, EURO1 | Cutoff, S
Raw Material Transport	<7	market for transport, freight, light commercial vehicle, EURO1 | transport, freight, light commercial vehicle, EURO1 | Cutoff, S
Production Energy Use	**Amount (MJ/kg)**	
Electricity from the grid	2.28	electricity voltage transformation from high to medium voltage | electricity, medium voltage | Cutoff, S
Heat from natural gas	5.32	heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical | heat, district, or industrial, natural gas | Cutoff, S
Packaging Materials	**Amount (kg)**	
Ethyl Vinyl Acetate	0.005	market for ethyl vinyl acetate, foil | ethyl vinyl acetate, foil | Cutoff, S
Polypropylene Fabric	0.031	market for polypropylene, granulate | polypropylene, granulate | Cutoff, S
	Amount (tons-km)	
Packaging Transport	>32	market for transport, freight, lorry >32 metric ton, EURO1 | transport, freight, lorry >32 metric ton, EURO1 | Cutoff, S
Packaging Transport	<7	market for transport, freight, light commercial vehicle, EURO1 | transport, freight, light commercial vehicle, EURO1 | Cutoff, S
Output	**Amount (kg)**	
SPE Base Oil	1	

- **SM 3: Biogenic Carbon Uptake Calculations**

Using *SPE* Base Oil VG-C.

The biogenic carbon uptake for a mixture of:

- Palm Kernel Fatty Acid (PKFA): 0.59975 kg
- Coconut Fatty Acid (CFA): 0.07351 kg

We assumed both fatty acids have similar carbon content since they are chemically close. The average carbon content for fatty acids from VG-C was 76% by weight.

Step 1: Estimate the Carbon Content in Each Fatty Acid

- Carbon in PKFA: 0.59975 kg×0.76 = 0.45581 kg C
- Carbon in CFA: 0.07351 kg×0.76 = 0.05587 kg C
- Total Carbon: 0.45581 + 0.05587 = 0.5568 kg C

Step 2: Convert to CO_2 Equivalents

Use the conversion factor from C to CO_2: 0.5568 kg C × (44/12) = 1.875 kg CO_2

Step 3: Apply Characterization Factor

Since this is biogenic uptake, apply −1 kg CO_2-eq per kg CO_2 taken up:

Biogenic CO_2 uptake = −1.875 kg CO_2

- **SM 4 – Environmental impact results and compared with LIGALUB and DITA. Result analyzed using EF 3.0 per kg of product.**

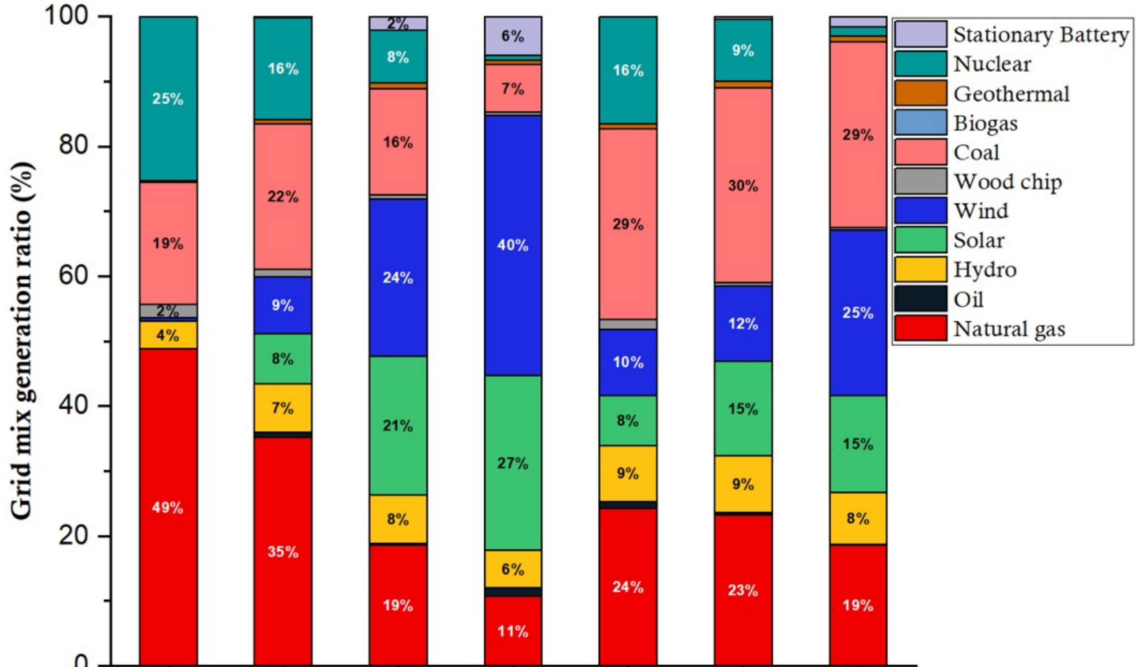
Table 2: LCA Results of the SPE base oil comparison based on EF 3.0. All values are in kg of product

Impact Categories	VG-A	VG-B	VG-C	VG-D	VG-E	VG-F	LIGALUB	DITA
GWP (kgCO_2-eq)	4.52	4.37	3.82	4.05	3.66	3.19	5.87	6.97
GWP (with bio. uptake) (kgCO_2-eq)	3.16	3.64	1.94	2.74	2.62	1.88	3.79	6.97
AP (mol H+ -eq)	3.36E-02	2.83E-02	1.77E-02	1.84E-02	2.04E-02	1.59E-02	2.83E-02	2.29E-02
EP (kg N-eq)	0.02422	0.0175	0.0131	0.0113	0.0096	0.0054	2.75E-02	3.38E-03
SP (kg NMVOC)	1.71E-02	1.58E-02	1.08E-02	1.18E-02	1.32E-02	1.16E-02	1.73E-02	1.92E-02
EF (CTUe)	404.97	392.32	251.44	287.45	287.72	221.15	-	-

Table 3: LCA Results of the SPE base oil based on TRACI 2.1. All values are in kg of product

	SPE Base Oils					
Impact Categories	VG-A	VG-B	VG-C	VG-D	VG-E	VG-F
GWP (kgCO_2-eq)	4.36	4.21	3.72	3.93	3.52	3.07
GWP (with bio. uptake) (kgCO_2-eq)	3	3.48	1.84	2.62	2.48	1.76
AP (kgSO_2-eq)	2.51E-02	2.17E-02	1.36E-02	1.45E-02	1.64E-02	1.33E-02
EP (kg N-eq)	4.60E-02	3.86E-02	2.36E-02	2.41E-02	2.66E-02	1.97E-02
EF (CTUe)	83.37	63.08	23	22.68	36.15	21.37
SP (kg O_3-eq)	2.96E-01	2.82E-01	1.83E-01	2.08E-01	2.47E-01	2.24E-01

- **SM 5 - Grid composition and lifecycle environmental impacts of electricity generation based on IMAGE Premise**



Scenarios	Current	SSP1_2030	SSP1_2040	SSP1_2050	SSP2_2030	SSP2_2040	SSP2_2050
GWP (kg CO_2-eq)	0.5508	0.4560	0.3015	0.1731	0.4767	0.4510	0.3757
AP (kg SO_2-eq)	1.25E-03	1.38E-03	9.57E-04	6.92E-04	1.43E-03	1.35E-03	1.17E-03
EF (CTUe)	1.30E+01	1.45E+01	1.41E+01	1.37E+01	1.46E+01	1.48E+01	1.49E+01
EP (kg N-eq)	1.83E-03	3.36E-03	2.14E-03	1.08E-03	3.52E-03	3.41E-03	3.09E-03
ODP (kg CFC-11-eq)	2.52E-09	2.06E-09	1.96E-09	2.01E-09	2.07E-09	2.12E-09	1.98E-09
SP (kg O_3-eq)	1.53E-02	1.38E-02	9.27E-03	6.38E-03	1.43E-02	1.33E-02	1.10E-02
PM (PM2.5-eq)	4.61E-04	1.80E-04	1.39E-04	8.61E-05	1.89E-04	1.82E-04	1.27E-04

Figure 2: Grid composition and lifecycle environmental impacts of electricity generation. The stacked bars show grid combinations by source for US-SERC for current scenario and USA SERC for SSP's as defined by the IAM's. Values are shown in percentages to represent the corresponding share of each energy source (e.g., natural gas, hydro, and wind) in the total electricity generation for the USA SERC. Only sources contributing more than 3% are labeled with their respective percentages in the chart. The table at the bottom presents the lifecycle environmental emissions for 1 kWh of low-voltage electricity delivered to the end-user side. The values include both direct emissions from the power plant and upstream emissions from the power plant and fuel production. Grid mix generation ratios for the current scenario are derived from the Ecoinvent 3.9.1 cutoff database, while SSP 1 and SSP2 are derived from the IAM IMAGE Premise databases.

SM 6 – Contribution Analysis

For the SPE base oil VG-C (**Figure 6A**), the most significant contributor to GWP is oleic fatty acid (44%), followed by proprietary polyol (30%) and electricity consumption (10%). This highlights the dominant role of biogenic feedstock and energy inputs in carbon emissions. In the case of AP and EP, proprietary polyol remains the largest contributor (32%), but the contribution from octanoic acid and its transport becomes increasingly significant, especially in EF, where octanoic acid accounts for 38% of the impact. For SP, emissions are primarily driven by proprietary polyol (42%), oleic fatty acid (27%), and transport-related processes.

SPE base oil VG-D (**Figure 6B**) shows a similar pattern but with slight variations in proportional contributions. GWP is primarily influenced by proprietary polyol (42%) and oleic fatty acid (35%), while electricity (9%) and heat consumption (4%) have modest but notable roles. Across AP, EP, and SP, proprietary polyol dominates (42–54%), underscoring its centrality in environmental burdens. Interestingly, the impact of ecotoxicity (EF) shifts, with oleic fatty acid contributing 18%, while octanoic acid processes account for another 18%.

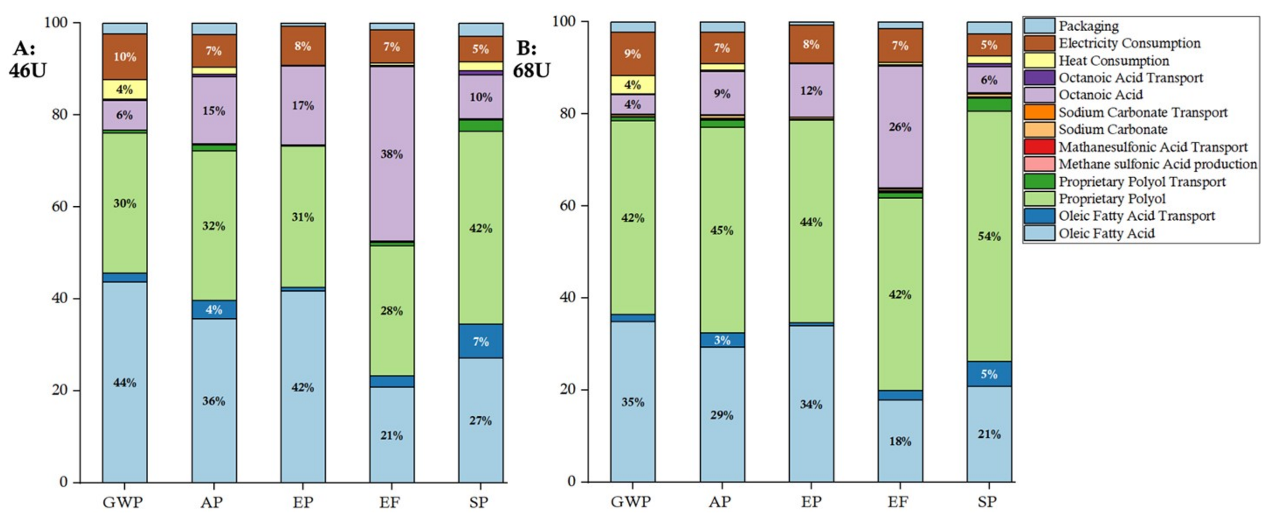


Figure 3: Process contribution in percentage for the SPE base oil VG-C and VG-D. Only processes contributing more than 2% are labeled with their respective percentages in the chart.

SPE base oil VG-E (**Figure 7A**), the primary contributor to GWP is polyol (55%), followed by octanoic acid (16%) and electricity consumption (10%). Similarly, polyol dominates AP and EP (46% each), while octanoic acid contributes significantly to EF (56%). Both polyol (53%) and isostearic fatty acid (15%) are major contributors to SP.

SPE base oil VG-F (**Figure 7B**), polyol also leads across impact categories, 54% for GWP and EP and 45% for EF. Isostearic fatty acid significantly affects AP (23%), EP (20%), and SP (27%), while electricity and heat consumption remain notable secondary contributors.

These results highlight that polyol production is the most environmentally intensive stage across both base oils. Its consistently high contributions across all categories suggest it is a key leverage point for improving environmental performance.

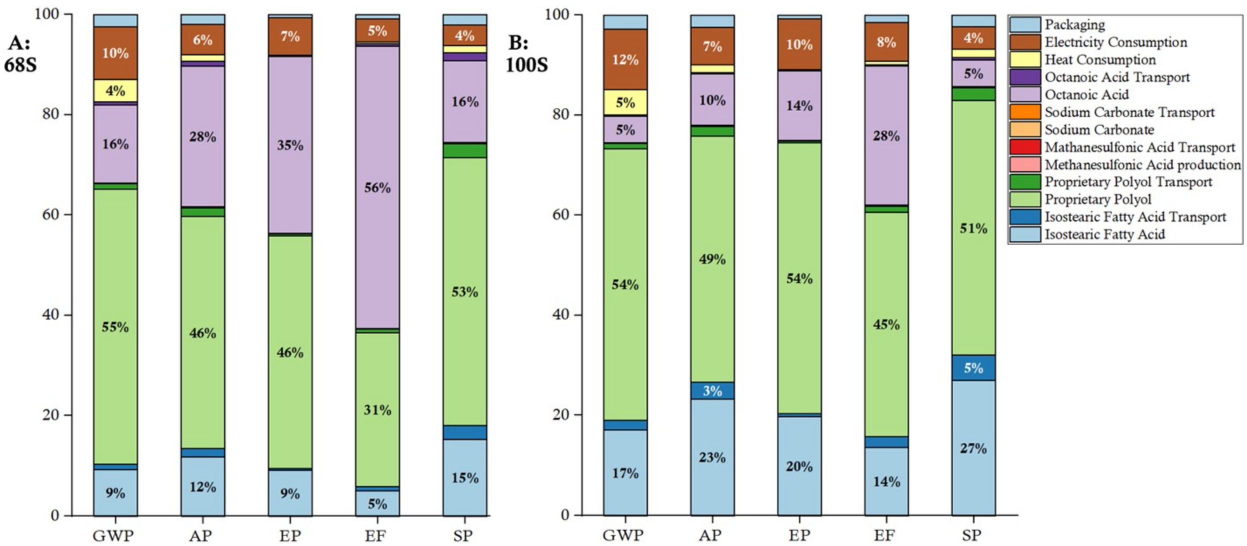


Figure 4: Process contribution in percentage for the SPE base oil VG-E and VG-F. Only processes contributing more than 2% are labeled with their respective percentages in the chart