Sustainability Benefits of Natural Ester Dielectric Fluid beyond Lifecycle Assessment

As a product derived essentially from renewable biobased sources, sustainability has always been one of the key drivers behind the rapidly growing market share of natural ester dielectric fluid particularly with the world increasing its push toward net zero carbon emission.

By Kin Yu LAM, Cargill Bioindustrial, Singapore

On the other hand, with governing bodies and the industries seeking to have more a holistic, robust and standardised approach in assessing environmental footprints, there are also some concerns that biobased products such as natural ester might have greater environment impacts on areas such as land and water use and ecotoxicity, etc. during the farming of the relevant crops. By examining the key issues concerning the lifecycle assessment of natural ester fluid and the relevant benefits it brings to the transformers, this article seeks to explain why with a fully integrated supply chain underpinned by robust environmental, social and governance (ESG) policies, natural ester fluid is indeed an effective solution that can contribute to achieving genuine sustainability in the power industry.

LIFECYCLE ASSESSMENT OF THE ENVIRONMENTAL IMPACTS OF DIELECTRIC FLUID

With continuous improvement in sustainability and, in particular, the reduction of the world's carbon footprint fast becoming a mandatory requirement for the key industrial and business segments, it is also increasingly important for the environmental impact of products to be established through lifecycle assessment (LCA). Due to the demand from end users, regulators and other stakeholders, the ISO 14040 and 14044 standards [1-2] were developed so that the environmental impacts of products can be assessed and verified under a holistic, standardised, and auditable framework.

Being one of key contributors to carbon emission and global warming, the power industry has long been obliged to reduce its carbon footprint at all fronts and the benefit of being inherently lower in carbon footprint is therefore increasingly becoming the key driver behind the high adoption rate of natural ester fluid in the industry. On the other hand, due to greater awareness of the wider scope of the use of LCA beyond assessing global warming potential, there is also concern that certain environmental issues related to natural ester fluid might have been overlooked particularly those related to the farming of the relevant crops. To provide a full picture regarding the sustainability benefits of natural ester, it is therefore necessary to consider both the carbon footprint of the fluid as well as the agricultural aspect of the crops.

Environmental benefits of natural ester as a biobased fluid

The key environmental benefits of natural ester are essentially based on its biobased and renewable nature. Deriving from plant crops growing on a yearly or seasonal basis as a product of photosynthesis, the biogenic carbon in the molecules of natural ester is originated from atmospheric carbon dioxide using entirely natural sunlight as the energy source. For this reason, the lifecycle carbon footprint of natural ester fluid is inherently much lower than other petroleum and synthetic fluids. In a LCA study on the most commonly used soybean oil based natural ester fluid, which covers raw material extraction and manufacturing from cradle to gate in accordance with ISO 14025 and 21930 [3-4], it has been shown that with the inclusion of biogenic carbon, a negative overall carbon footprint can be achieved over and above the carbon emission contributions from fossil fuel consumption and land use change (Table 1) [5].

Biobased carbon content	Total carbon emission including biogenic carbon (kg CO_2 equivalent per kg)	Carbon emission from fossil fuel excluding biogenic carbon (kg CO_2 equivalent per kg)	Carbon emission from land use and land use change (kg CO_2 equivalent per kg)
99.1%	-0.74	0.82	0.012

Table 1 *Cradle to gate product carbon footprint of FR3® natural ester fluid (soybean oil based) manufactured at the Cargill facility in Chicago, USA [5]*

Although technically petroleum based mineral oil is also originated from biomass, its nonrenewable nature means that there is no biogenic carbon to offset its carbon footprint. For this reason, increasingly both the power and oil industries are actively promoting recycling of mineral oil amid the drive toward net zero carbon emission. While the use of recycled mineral oil would help to reduce carbon footprint and the depletion of oil reserve, there are concerns that some of the reclaiming processes might not be sufficient to restore the quality of virgin mineral oil, and some of the more advanced re-refining technologies might be more energy intensive and therefore reduce the benefit of recycling.

As for natural ester fluid, technically it is also feasible to be reclaimed and recycled in similar way to mineral oil. On the other hand, since natural ester has only been used commercially as a dielectric fluid for over 25 years, the limited number of natural ester-filled transformers reaching end of service life means that the demand of fluid recycling is still very much at the infancy stage, possibly making it less commercially viable. From an environmental perspective, it is also less critical to recycle natural ester fluid for use in transformers due to its biobased and renewable nature as described earlier. Since the reclamation process would inevitably require energy input, it is likely that any recycled natural ester fluid would have higher carbon footprint than the original virgin fluid. As used vegetable oil is also widely used as raw materials for the manufacturing of soaps, industrial chemicals, and biofuels, etc., it would probably be more feasible to reclaim used natural ester fluid for such industries.

Environmental impact of farming for natural ester fluid

While understandably carbon footprint has been the most focused aspect of environmental sustainability given the criticality and urgency to combat global warming, increasingly the wider environmental impact concerning the agriculture of crops for natural ester is also becoming an area of concern due to issues such as deforestation and the degradation of land and water resources, etc.

Although it is necessary to consider the impacts of agriculture in areas such as water intake, eutrophication, acidification and ecological toxicity, etc. to have a holistic view on the environmental footprint of natural ester, it is also important to evaluate such data in the context of the total value of crops and the relevant environmental, social and governance aspects of the entire supply chain.

Continued on page 128

Trust the Original and Most Proven Natural Ester

FR3® fluid is the original, most tested and proven natural ester in the world. Used for nearly 30 years in over 3.5 million distribution and power transformers and validated through hundreds of field and laboratory tests, FR3 natural ester continues to be trusted by leading OEMs and transformer users around the globe. Derived from over 95% renewable vegetable oil, FR3 natural ester outperforms mineral oil resulting in more reliable, higher performing, and more sustainable transformers. It's the smartest choice in dielectric fluids – for performance, value, and peace of mind.

Exceptional Reliability

- Continuously dries paper insulation without creating any damaging byproducts or sludge for up to 8X longer paper insulation life*
- Easily handles high heat with up to 140°C top fluid temperature**

More Sustainable

- 100% biodegradable in as little as 10 days
- Non-toxic in water, soil, and to wildlife and humans
- Reduce dependency on fossil-based materials in your transformers

Increased Loading Capacity

- Up to 20% more loading capacity compared to mineral oil without impacting transformer lifespan
- Design a smaller transformer with the same loading capacity, the same sized transformer with up to 20% more loading capacity, or any combination in between*

Superior Fire Safety

- 0 reported fires in over 25 years
- K-class fluid with over 2X higher flash and fire points compared to mineral oil (360°C fire point)

Cost Savings

- Design a smaller, more power dense transformer and save on expensive materials like steel, aluminum, copper and insulating paper
- Remove or greatly reduce expensive fire remediation and spill containment systems because of K-class fluid certification and 100% biodegradability

*Compared to mineral oil
**According to IEC 60076-17, IEEE C57-154

FR3
a Cargill brand

Continued from page 126

One of the common pitfalls in some of the LCA studies is overlooking the fact that the agriculture of common crops is not solely for the manufacturing of natural ester dielectric fluid. For example, although the yield of soybean oil, a common base oil for natural ester fluid, is only about 18%, most of the remaining portion of soy crop is soy meal which is most important to the global animal feed and food industries as a major source of protein and carbohydrate [6]. In other words, if one only attributes the environmental impact of soy farming entirely to natural ester fluid in the LCA without considering the major output of soy meal, it will grossly exaggerate the agricultural impact and give a very misleading picture of its environmental footprint.

Another common shortcoming in some of the LCA studies is the over reliance on industrial data that fails to recognise the vast difference in environmental impact among natural ester fluids from different suppliers. For example, with a fully integrated supply chain, suppliers such as Cargill would have sourcing control to effectively minimise the impact of deforestation for its soy crops and therefore greatly reduce the lifecycle environmental impact of its natural ester fluid [7]. More importantly, close contact with the local farming communities would also allow companies like Cargill to actively promote responsible farming globally to protect, regenerate and restore land and water resources with clearly defined and forward-looking sustainability goals (Table 2).

In summary, although comparison of the generic LCA data obtained from secondary industrial sources for different types of dielectric fluids might be informative as general reference, it is no doubt from the discussion above that only primary data from suppliers with robust integrated supply chain underpinned by sound environmental, social and governance (ESG) policies would be truly valuable in enabling end users to track and continuously improve the carbon footprint and overall sustainability of their operation.

Criteria	Target metrics	Progress by 2023
Climate	Reduce scope 1 and 2 (operations) greenhouse gas (GHG) emissions by 10% by 2025	-10.97% reduction from 2017 baseline
	Reduce scope 3 (Supply Chain) global GHG emissions by 30% by 2030 (for per ton of product)	-0.43 million ton of CO2 equivalent reduced through supply chain sustainability programs
Land use change	Eliminate deforestation across our agricultural supply chain by 2030	Deforestation and conversion free: Argentina – 98% Bolivia – 73% Brazil – 94% Paraguay – 96% Uruguay – 100%
Water use	Operations: Implement water stewardship practices at all 72 priority facilities by 2025	78%
	Supply Chain and Communities: Enable a water positive impact in all priority regions by 2030	8.6%

Table 2 *Cargill's key sustainability goals relevant to the improvement of the lifecycle environment impacts of its natural ester fluid [7]*

Failure mode	Percentage of cases [i]	Impact of natural ester on failure (a) [ii]	Reduction in degradation rate (b) [ii]	Rate of failure for mineral oil-filled transformers (c) [iii]	Rate of failure for natural ester-filled transformers [iv]
Dielectric	36.62%	85%	7.4x	1.43%	0.38%
Electrical	16.49%	0%	0	0.64%	0.64%
Thermal	10.89%	100%	4x	0.42%	0.11%
Physical chemistry	3.32%	75%	2x	0.13%	0.08%
Mechanical	20.02%	0%	0	0.78%	0.78%
Unknown	12.66%	0%	0	0.49%	0.49%
Total	**100%**	-	-	**3.89%**	**2.48%**

i. Figures from CIGRE Technical Brochure on Transformers Reliability Survey [15]
ii. Benefits of using natural ester fluid based on each failure mode's relevance to insulation degradation
iii. Based on the total annual failure rate of 3.89% and the percentage of each failure mode
iv. Rate of failure of natural ester-filled transformers calculated from: c(1-a) + ac/b

Table 3 *Estimated annual failure rates by failure modes for mineral oil and natural ester-filled transformers [10]*

Transformer replacement cause	Percentage of cases	Impact of natural ester on replacement rate	Replacement rate for mineral oil-filled transformers	Replacement rate for natural ester-filled transformers
Random	5%	0%	0.24%	0.24%
Increase in demand	15%	50% [v]	0.73%	0.37%
Transformer failure	80%	Refer to Table 3	3.89%	2.48% [vii]
Total	**100%**	-	**4.87%** [vi]	**3.09%**

v. Based on additional loading capacity of natural ester filled transformers which reduces replacements due to increase in demand
vi. Annual replacement rate for mineral oil filled transformers based on nominal transformer life of 20.55 years (180,000 hours)
vii. Transformer failure rate of natural ester filled transformers obtained from Table 3.

Table 4 *Estimated annual replacement rates for mineral oil and natural ester-filled transformers [10]*

SUSTAINABILITY BENEFITS FROM IMPROVED DURABILITY AND LOADING CAPACITY OF NATURAL ESTER-FILLED TRANSFORMERS

While robust LCA data is critical to evaluate environment footprint of products, it is worth mentioning that natural ester's ability to prolong insulation life and to increase loading capacity of transformers is also extremely important in delivering sustainability benefits to the power industry far beyond a mere biobased product can offer.

Economic and environmental benefits from longer insulation and transformer life

As recognised in both the IEC and IEEE standards for high temperature insulation system [8-9], the use of natural ester fluid can extend the lifespan of cellulose-based paper insulation by up to 8 times. In a study conducted with a major American utility on a fleet of 96,000 transformers [10], the benefit of transformer life extension with natural ester fluid was evaluated based on the nominal lifespan of mineral oil-filled transformers as per the IEC loading guide [11] and the percentages of various transformer failure modes as stated in the CIGRE Transformer Reliability Survey [12]. The analysis of the relevant data concluded that with the longer insulation life in natural ester-filled transformers, the annual failure rate can be reduced from 3.89% to 2.48% (Table 3), and the overall replacement rate reduced from 4.87% to 3.09% (Table 4), resulting in a 58% extension in nominal transformer life from 20.55 years to 32.38 years.

Net present values of the total ownership costs of transformers calculated with the relevant equipment, operational and financial parameters from the utility confirms the positive savings due to the extended transformer life expectancy for the different sizes of natural ester-filled distribution transformers based on both continuous (perpetuity) and limited (expected lifespan of natural ester-filled transformer) timeframes, offsetting the higher initial costs of natural ester-filled transformers (Table 5) [10].

From an environmental perspective, the longer life expectancy of natural ester-filled transformers would obviously bring additional sustainability benefits primarily from the lower equipment replacement rate which effectively reduces the consumption of non-renewable raw materials and energy associated to the manufacturing of new transformers.

Sustainability benefits from transformer design

Apart from the extension of transformer life, increasingly the power industry is also exploring new ways to utilise the higher loading capacity of natural ester-filled transformers to deliver energy and material efficiency benefits.

Based on the principle of electrical engineering, there is an inherent conflict trying to improve both energy and material efficiencies of transformers since it is necessary to increase the amount of conducting material to reduce energy loss from heat dissipation. However, with the variability of loading profile and the higher loading capacity of natural ester-filled transformers, it is possible to overcome such a constraint based on the sustainable peak loading design [13-14].

According to the Transformer Ecodesign Preparatory Study in Europe, the average load factor for distribution transformers in public network is estimated to be around 15% only [15]. The low level of utilisation is considered necessary due to the need to maintain redundancy and reliability, and for the transformers to handle the peak rather than the average demand. While such design approach would enable the public network to cope with occasional simultaneous load switching, component failure and other emergency conditions, as well as the anticipated growing demand for electricity, it would also lead to lower energy efficiency due to the high no-load loss from the oversized transformers.

Transformer rating (kVA)	Transformer cost (US$)		Net present value saving (US$)	
	Mineral oil-filled	Natural ester-filled	Perpetuity horizon	Transformer life horizon
25	2,333	2,726	862	378
50	3,293	3,759	1,144	513
75	4,175	4,651	1,459	718
100	5,537	6,123	1,853	900
167	8,267	9,111	1,853	900

Table 5 *Net present value savings from 58% life extension for natural ester-filled transformers based on study with a US utility [10]*

Since transformers are usually not built just to match temperature limits due to other restrictions such as total losses limitation, the 20°C higher temperature rise limits for natural ester-filled transformers with TUK paper would normally allow a 35-50% increase in loading capacity based on the same hardware design. Utilising this benefit of increased loading capacity, the sustainable peak loading design is essentially about deploying a natural ester-filled transformer to replace a conventional mineral oil-filled unit one nominal rating grade higher while maintaining the top oil and hottest spot temperatures within the limits of the higher insulation thermal class.

Based on a case study from a major transformer OEM, the significant environmental and economic sustainability benefits from using sustainable peak loading transformers in distribution network can be clearly demonstrated [16]. As shown in Table 6, when an 800kVA natural ester-filled transformer is deployed in place of a 1000kVA conventional mineral oil-filled unit with an average load factor of 27%, about 58 MWh of power can be saved from energy loss over the nominal transformer life of 30 years, resulting in a total reduction of carbon emission equivalent to 30 MT of carbon dioxide per transformer. With consideration to the cost of energy loss and potential environmental cost, it was estimated that over 11% of saving on total ownership cost can be achieved with the sustainable peak loading transformers using natural ester fluid.

Parameters	1000 kVA mineral oil-filled transformer	800 kVA natural ester-filled transformer
No-load loss (NLL) (W)	770	585
Load loss at rated load (LL) (W)	9,000	6,000
No-load loss/year (kWh)	6,745	5,125
Load loss/year (kWh) [a]	5,747	5,724
Total loss/year (kWh) [a]	12,493	10,848
Total loss over 30 years (MWh)	375	325
Equivalent CO_2 emission over 30 years (tons) [b]	228	198
Transformer cost (US$)	35,000	32,000
Cost of energy loss over 30 years (US$) [c]	27,980	24,296
Environmental cost over 30 years (US$) [d]	11,412	9,896
Total ownership cost over 30 years (US$) [e]	74,980	66,700

Transformer load loss calculated at average load factor of 27%
Carbon emission rate for power generation assumed to be at 0.608 MT CO_2 equivalent per MWh
Calculated from no-load loss and load loss capitalization factor at US$19,619 and US$1,430 per kW respectively over 30 years
Environmental cost at US$50 per MT CO_2 equivalent
Total sum of transformer cost, cost of energy loss and environmental cost

Table 6 *Energy efficiency and carbon emission benefits of an 800kVA natural ester-filled sustainable peak loading transformer against a conventional 1000kVA mineral oil-filled transformer at 27% load factor [16]*

Apart from energy efficiency improvement, a further sustainability benefit can also be derived from the sustainable peak loading natural ester-filled transformers due to the smaller equipment size which reduces the use of non-renewable materials. According to a study conducted by European Copper Institute, about 400,000 MT of steel and 200,000 MT of aluminum can be conserved across Europe just by replacing all the 400 kVA distribution network transformers with dual-rated 400/538 kVA natural ester-filled units of the sustainable peak loading design instead of the conventional 540 kVA units over the period of 2020-2050 (Table 8) [17].

	540 kVA mineral oil transformer	400/538 kVA natural ester transformer	% Reduction with dual-rated units
M0H steel (1,000 ton)	2877	2495	13%
Aluminum (1,000 ton)	1158	960	17%
Liquid (1,000 m^3)	1422	1301	-
Total weight (1,000 ton)	7304	6513	11%

Table 7 *Materials consumption for replacing all 400kVA public distribution network transformers in the EU over the period of 2020-2050 with conventional and sustainable peak loading units [19]*

NATURAL ESTER DIELECTRIC FLUID PROVIDES SUSTAINABILITY BENEFITS

As the industry becomes increasingly aware of lifecycle assessments on environment footprints beyond carbon emission and some of the issues related to land and water use in agriculture, there are inevitably some concerns raised over the potential impact of using biobased products including natural ester fluid. However, as discussed earlier with the support of additional robust primary LCA data backed up by a fully integrated supply chain and robust ESG policies, natural ester fluid will no doubt continue to be considered as a more sustainable fluid of choice among the discerning end users. More importantly, as more and more transformer OEMs and end users seek to take advantage of the benefits of extending transformer life and loading capacity, the use of natural ester will certainly leave an even greater impact in the sustainability journey way beyond what the LCA shows.

References

1. *ISO 14040 – 'Environmental Management – Life Cycle Assessment – Principles and Framework', International Organization of Standards, Geneva, Switzerland, 2006.*
2. *ISO 14040 – 'Environmental Management – Life Cycle Assessment – Requirements and Guidelines', International Organization of Standards, Geneva, Switzerland, 2006.*
3. *'Product Carbon Footprint of FR3® Natural Ester Fluid', Cargill Bioindustrial, 2024.*
4. *ISO 14025 – 'Environmental Labels and Declarations – Type III Environmental Declarations – Principles and Procedures', International Organization of Standards, Geneva, Switzerland, 2006.*
5. *ISO 21930 – 'Sustainability in Buildings and Civil Engineering Works - Core Rules for Environmental Product Declarations of Construction Products and Services', International Organization of Standards, Geneva, Switzerland, 2017.*
6. *'Understanding Soybean Crush', Introduction to Agriculture, CME Group, Chicago, IL, U.S.A. Available online: https://www.cmegroup.com/education/courses/introduction-to-agriculture/grains-oilseeds/understanding-soybean-crush.html*
7. *2023 Cargill Global Environmental, Social and Governance (ESG) Report. Available online: https://www.cargill.com/sustainability/2023-esg-report*
8. *IEC 60076-14 - 'Liquid-Immersed Power Transformers Using High-Temperature Insulation Materials', International Electrotechnical Commission, Geneva, Switzerland, Sep 2013.*
9. *IEEE 1276 - 'Guide for the Application of High-Temperature Insulation Materials in Liquid-Immersed Distribution, Power, and Regulating Transformers', Institute of Electrical and Electronics Engineers, Inc., New York, USA, 2020.*
10. *C. V. Vaidya, G. G. Karady, A. Sbravati, J. Valmus and M. Dyer, 'Evaluation of High Temperature Operation of Natural Ester Filled Distribution Transformers', 2018 North American Power Symposium (NAPS), 2018, pp. 1-6.*
11. *IEC 60076-7 - 'Loading guide for mineral-oil-immersed power transformers', International Electrotechnical Commission, Geneva, Switzerland, Sep 2018.*
12. *'Transformer reliability survey', in Technical Brochure 642, CIGRE Working Group A2.37, CIGRE, Paris, France, December 2015.*
13. *C. Alberto, F. Nuño, and R, Fernández. 'Modelling the potential of enhanced capacity transformers for optimizing material efficiency and asset utilization', 27th International Conference on Electricity Distribution (CIRED 2023). Vol. 2023. IET, 2023.*
14. *R. Fernández, A. Sbravati and A. Cracco, 'Sustainable Peak Loading Capacity Transformers', 2022 IEEE 21st International Conference on Dielectric Liquids (ICDL), Sevilla, Spain, 2022, pp. 1-4.*
15. *VITO for European Commission DG ENTR unit B1, 'Lot 2: Distribution and Power Transformers, Task 1-7', January 2011.*
16. *B. P. Das and S. Patel, 'Ester-filled Distribution Transformers - The Sustainable Model to Strengthen the Low Voltage Grid', Transformers Magazine, pp30-42, Vol 9, Issue 1, 2022.*
17. *Bruno De Wachter, 'Whitepaper – Maximizing Distribution Transformer Resource-Efficiency/Potential Contribution to EU Green Deal Objectives', Publication Cu0277, European Copper Institute, October 2021.*

For more information visit:
www.cargill.com