FACT SHEET

# MEDIUM-POWER TRANSFORMER RECYCLABILITY

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October 2021

ECI Publication No Cu0278

## Document Issue Control Sheet

| | |
|---|---|
| Document Title: | Fact sheet – Medium power transformer recyclability |
| Publication No: | Cu0278 |
| Issue: | 01 |
| Release: | Public |
| Content provider(s) | Tomas Jezdinsky, Angelo Baggini |
| Author(s): | Bruno De Wachter and Tomas Jezdinsky |
| Editorial and language review | |
| Content review: | Tomas Jezdinsky, Fernando Nuno, Angelo Baggini |

## Document History

| Issue | Date | Purpose |
|---|---|---|
| 1 | October 2021 | Initial public release |
| 2 | | |
| 3 | | |

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**Acknowledgment**

*First, a special word of thanks goes to all the companies participating in the transformer recycling survey. Without their commitment to collaboration and openness in sharing knowledge and expertise it would not have been possible to produce this fact sheet. Their contributions are greatly appreciated. The full list of participating companies can be found at the end of this document.*

# Executive summary


Recent EU policy initiatives in the slipstream of the Green Deal promote a systematic approach to material efficiency and recyclability in product design. In this respect, medium-power electrical transformers are an interesting case on which to focus. The Copper Alliance conducted an in-depth survey of the current state of transformer recycling, revealing a sharp contrast between liquid-filled and dry type units.

Liquid-filled medium-power transformers have a high degree of circularity at end-of-life, with about three quarters of the material compatible with an entirely circular process. This potential is fully exploited thanks to the fact that only certified companies are allowed to handle liquid-filled transformer recycling, which is a positive legacy of the PCB crisis.

About 70% of the mineral oil is recycled for re-use, and the remaining 30% is re-used as a second-grade oil in other applications. Natural esters, now increasingly used as an insulating liquid, could in principle be recovered in the same way as mineral oil, but the market, equipment, and technical standards to govern this process are still lacking.

Close to 100% of aluminium from windings is recycled in second-life products, for which 98% purity is adequate. The existence of different alloys on the market and impurities in the scrap are a barrier to first-grade aluminium recycling.

The degree of circularity of a liquid-filled transformer can be enhanced by using copper for the high voltage winding. The vast majority of copper winding shreds are recycled at the highest purity level (99.9%). The copper can be melted down and used again for electrical applications, including transformer windings, without further purification. Copper windings also increase the end-of-life value of the unit, enhancing the business case for recycling and re-use.

Magnetic steel from the transformer core, as well as structural steel parts, are almost 100% recovered. The magnetic steel laminates can, in principle, be cleaned and re-used, but the transformers currently being taken out of service have laminates that are too thick to comply with the Ecodesign regulation. Some of this goes to make laminates in Asia and Turkey where smaller transformers are not subject to loss restrictions. The remaining steel laminates and structural steel elements are smelted and used for the industrial production of new steel (first-grade recycling).

Dry type transformers follow a totally different recycling route and demonstrate how a lack of separability in the conception of a device can lead to a problematic end-of-life process. Their coils are overmoulded with an epoxy or quartz resin that is hard to separate from the metal conductors. The separation process is not economically viable in the EU because it is time and energy consuming, and only results in low purity metal scrap. The coils are sold with other electromechanical scrap for export outside the EU, where a lower-paid workforce separates the resin from the aluminium coils in semi-automated processes.

## THE REGULATORY CONTEXT OF TRANSFORMER RECYCLING

The concepts of *material stewardship* and *design-for-recycling* are rapidly growing in importance. In its *Green Deal*, published in December 2019, the EU emphasized that its decarbonization ambition should be accomplished with maximum resource efficiency. This theme was developed further in a new *Circular Economy Action Plan*, published in March 2020. The revised *Methodology for Ecodesign of Energy-related Products* (*MEErP*), in July 2021, translated the ambition into concrete decision-making instruments, facilitating the systematic inclusion of material efficiency parameters — including recyclability — in design decisions for energy-related products.

Note that design-for-recycling will always be subject to major uncertainties when applied to devices with a very long lifetime, such as transformers. It is impossible to accurately predict where the recycling market and technology will be 40 years from now. Moreover, the feasibility of re-using parts at end-of-life will depend on the transformer technology and regulations in vigour at that time, which is equally difficult to predict. What can be done, however, is to make an approximative assessment of the recyclability and circularity of transformer parts and materials based on an analysis of today's technology and market.

## SCOPE

This fact sheet will focus on medium-power transformers, which are defined by EU Commission Regulation 2019/1783 as transformers with a rated power lower than or equal to 3,150 kVA, and primary voltage greater than 1.1 kV and lower than or equal to 36 kV. These transformers are used in electricity distribution networks, in industry, or for the connection of distributed energy resources (DER). The transformers discussed here have copper or aluminium as a conductor material for the windings and M0H, M3 or amorphous magnetic steel. Liquid-filled and dry type transformers have very different recycling parameters, covered here by separate chapters. The insulation liquids discussed here are mineral oil and natural esters. Other types of liquid insulation with a minor market share are not the subject of this analysis.

RECOTEX)

## SOURCES

20 in-depth interviews with stakeholder companies on current practices in transformer recycling form the basis of this fact sheet. These companies include distribution system operators (DSOs), transformer maintenance companies, transformer recycling companies, and specialist transformer oil recycling companies in Germany, Spain, Italy, France and Serbia. Data from the survey were collected and approved following the Delphi method, except where otherwise referenced. A full list of the interviewed companies can be found in the Annex.

## The transformer life cycle

Medium-power transformers remain in use for a very long time. The depreciation period is typically 40 years, but their actual lifetime is much longer — usually more than 50 years and sometimes even 80 years [1, p.4-5].

At end-of-life, the transformers must be handled by certified recycling companies who are empowered to issue the required legal documentation. In theory, this task could be shared by multiple companies, but the great majority of end users rely on a single recycling company (one-stop-shopping). In practice, this recycler will often use specialist sub-contractors for tasks such as oil separation and recovery, or transporting large transformers by rail or road.

Liquid-filled transformers are disassembled much in the same way as they were assembled. Smaller units are usually disconnected by the end-user and shipped in their entirety to the recycling plant. Larger units are first treated in situ by trained recycling company staff. The oil is pumped out and the transformer is dismantled to its core components, which are then shipped to the recycling plant for further separation.

Dry type transformers follow a different route at end-of-life. The main components are disassembled and sold to scrap and metal dealers for further separation. The coils, which are hard to recycle since they are entirely covered with cast resin or other polymers, are usually sold for export outside the EU. The remaining parts, such as the magnetic core and the frame, are dismantled much in the same way as liquid-filled transformers.

## MATERIAL RECYCLING OF LIQUID-FILLED TRANSFORMERS

In theory, some 90 - 95% of every transformer could follow an entirely circular recycling route. The materials can be recovered and re-used in new transformers, or recycled into the same material needed for the manufacture of new transformers. In practice, some of the material will be downgraded for use in second-life products with lower purity requirements, where the circular route is technically complicated and economically unfeasible. This includes all the aluminium and about 30% of the oil content. Replacing aluminium conductors with copper increases the degree of circularity, since most of the copper is recovered with very high purity for re-use as electrical conductor material. Only a small proportion of end-of-life transformer material is incinerated with heat recovery (3 - 5%) or ends-up in landfill (1 - 2%).

## OIL RECYCLING

### MINERAL OIL

In principle, mineral transformer oil can be recovered almost entirely (>99%) for re-use in transformers through a filtering process. In practice, about 70% of the mineral transformer oil is recycled as first-grade for re-use in transformers, and the remainder is re-used as second-grade oil in other applications — mainly as industrial lubricants.

There is an issue with PCBs, formerly added to mineral oil to increase its fire resistance. When the PCB content in the oil is beyond 50 ppm it must be considered as hazardous waste, triggering very strict safety rules for handling and treatment. For this reason, the liquid transformer recycling process now begins with an oil analysis, and only certified companies are allowed to deal with liquid-filled transformer recycling. PCBs were completely banned in the EU in 1987, since they were found to have a far-reaching impact on human and animal health. No new transformers containing PCBs have been brought into use in the EU since that date. Consequently, the issue of PCBs for transformer oil recycling is expected to fade in the next 20 years.

### NATURAL ESTERS

In principle, natural esters could be recovered much in the same way as mineral oil.

In practice, the market and equipment for recycling natural esters is still lacking, because its widespread use in transformers is recent and the number of natural ester transformers reaching end-of-life is still negligible. Moreover, the current international quality standard for natural esters (IEC 62770) takes only unused liquids into account, without considering liquids originating from recycling. This is in contrast with the standard for mineral oils (IEC 60296 ed5), which sets quality requirements regardless of the oil's origin. As a result, there is as yet no first-grade recycling process for natural esters.

An estimated 20 - 30% of natural esters are currently subject to second-grade recycling. They are considered to be high quality vegetable oils which can be used as industrial lubricants or as process agents in a wide range of applications, such as paints, coatings, and soaps. Natural esters can also be mixed into biodiesel [2, p. 79]. The remaining 70 - 80% of the natural esters from end-of-life transformers is currently incinerated with heat recovery.

A more efficient market for natural ester recycling, or potential re-use, is expected to develop when more transformers using this innovative liquid insulation have reached end-of-life.

### OIL IMPREGNATED INTO OTHER ELEMENTS

The preceding figures for mineral oil and natural esters do not include the liquids impregnating the paper and wood in contact with the oil bath. Over a transformer's lifetime, the quantity of oil "disappearing" in this way can be as high as 4 - 5% of the total oil volume. In theory, this liquid could be separated from the solid waste using a centrifuge or autoclave, but this is hardly ever done in practice, since it is not worth the cost for such a relatively low-end product. Consequently, this part of the oil usually ends up being incinerated with energy recovery, along with the paper or wood.

## METAL RECYCLING

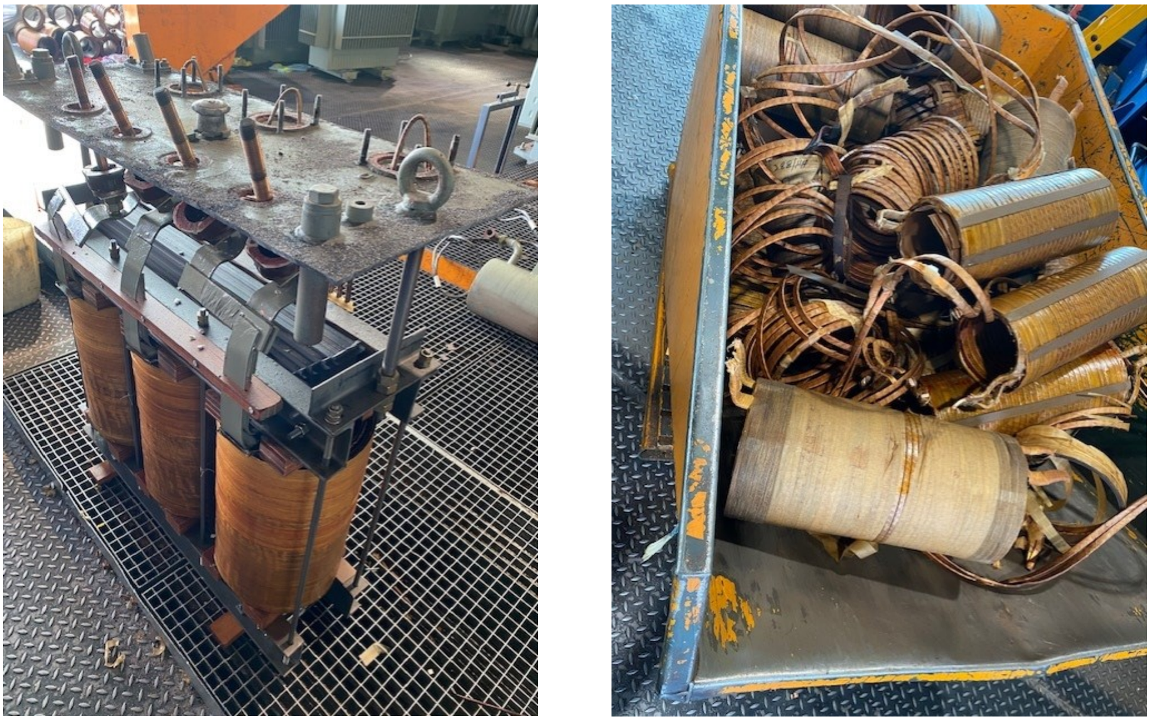

**FIGURE 2 – A DISMANTLED TRANSFORMER CORE, AND TRANSFORMER COILS READY FOR RECYCLING** (COURTESY: RECOTEX)

**FIGURE 3 –MAGNETIC STEEL LAMINATES AND COPPER GRANULATE** (COURTESY: RECOTEX)

### COPPER

The copper used in transformers can be almost 100% recovered.

The copper winding is shredded before being sorted to remove the small amounts of impregnated paper and lacquer. The copper pieces are then recycled at three different purity levels: level 1A with minimum 99.9% purity, level 1B with minimum 99.7% purity, and level 2 with minimum 95.0% purity. How much of the copper exactly goes into each of those purity levels depends on the recycling company, but most (> 90%) will be recycled at level 1A. One company has stated that it recycles 97% of the copper from transformer windings at the highest purity.

Purity level 1A (>99.9%) has the same quality as copper cathodes. It can be melted and used again for electrical applications, including transformer windings, without further purification. This means that it follows a truly circular route that is highly efficient in terms of cost, energy use and environmental impact.

Purity level 1B (>99.7%) has the same quality as copper anodes. It must be subjected to an electrolysis process to reach the purity level required for electrical copper.

Purity level 2 (>95.0%) has the same quality as the copper concentrate sold by mining companies. It would need to undergo a thermo-chemical process to reach level 1B, and subsequently be subjected to an electrolysis process to reach level 1A, the purity level required for the electrical copper. In practice, it rarely follows this trajectory, and is used without further purification in applications that require lower purity, such as copper alloys (e.g. brass) or additives in steel making.

### ALUMINIUM

The aluminium used in transformer windings can be almost 100% recovered.

In theory, this aluminium could then be recycled with purity levels of up to 99.7% (Alu 7), which is the required level for re-use in new aluminium electrical wire manufacturing. In practice, however, the fact that it exists in many different alloys poses a serious barrier. The material should be subjected to laboratory analysis to detect the alloys and could then be recycled for use only in exactly the same kind of electrical application as previously. This is technically and organizationally complicated, and is never carried out in practice.

Because of the presence of the alloy materials and other contaminating metals (e.g. copper from connectors), the purity levels of the aluminium from transformer windings do not get any higher than 98%. The material is downgraded for use in second-life products for which this purity level is sufficient, such as building materials or non-electrical automotive parts.

### STEEL

Magnetic steel from the transformer core and structural steel parts from the frame are almost 100% recovered.

Magnetic steel laminates can in principle be cleaned and re-used in a new transformer. However, the transformers currently being taken out of service in the EU have laminate thicknesses of 0.3 mm and above, which no longer comply with the current Ecodesign regulation. Some goes to be stamped out to make laminates in Asia and Turkey where smaller transformers are not subject to loss restrictions. [3]. The process of stamping out smaller laminates from the original piece also has the advantage that potential damage from the dismantling process at the laminate edges is not an issue. The proportion of magnetic steel following this route depends on prices in the Asian market.

If transformers reaching end-of-life were to comply with the prevailing Ecodesign regulations, there would be no reason why the steel laminates could not be similarly re-used in the EU.

Any steel laminates not exported and re-used, as well as the structural steel parts, go to scrap. 100% of the steel scrap is smelted and used for the industrial production of new steel.

## OTHER MATERIALS

Porcelain elements used for electrical insulation in various parts of the transformer are sorted, cleaned and shredded. Almost 100% is used in construction, mainly as hardcore in road construction.

About 3 - 5% of a transformer is organic material such as wood, paper, or corrugated cardboard. Much of this has been impregnated with oil by transformer end-of-life. As discussed earlier, this liquid could in principle be separated from the solid waste for re-use, but this is not economically viable. As a result, these materials, with the oil they contain, go to waste incineration plants with energy recovery. This means that they are used as a combustion material to generate heat or electricity. In some EU countries, a lack of incineration plants or legal constraints mean that these elements end up in landfill.

A small proportion of the transformer (1 - 2%) cannot be re-used, recycled, or incinerated, and has to be disposed of in landfill. This includes plastic joints and buffers, and silica connectors.

## A TYPICAL CASE

A 400 kVA liquid-filled distribution transformer, containing PCB-free mineral oil, M0H magnetic steel, aluminium low voltage winding, and either aluminium or copper for the high voltage winding, would typically have the following bill of material [4]:

| Technology | With aluminium in HV winding | With copper in HV winding |
|---|---|---|
| Effective rating (kVA) | 400 | 400 |
| LV/HV winding | Al/Al | Al/Cu |
| Liquid type | Mineral oil | Mineral oil |
| Steel type | M0H | M0H |
| **Bill of material** | | |
| Magnetic steel (kg) | 1056 | 1018 |
| Aluminium (kg) | 273 | 93 |
| Copper (kg) | 0 | 482 |
| Liquid (litres) | 519 | 579 |
| Porcelain (kg) (1%) | 26 | 30 |
| Wood, paper, cardboard (kg) (5%) | 131 | 149 |
| Structural steel (kg) | 569 | 575 |
| Other parts (kg) (2%) | 53 | 60 |
| **Total weight (kg)** | **2627** | **2986** |

**TABLE 1 – BILL OF MATERIAL OF A TYPICAL DISTRIBUTION TRANSFORMER**

The figures for “wood, paper, cardboard” and for “other parts” are based on information derived from the market study discussed earlier.

Based on data from the same market study, the degree of circularity of the various materials of the transformer would be as follows:

| | 400 kVA, M0H, mineral oil, aluminium in HV winding | | 400 kVA, M0H, mineral oil, copper in HV winding | |
|---|---|---|---|---|
| **End-of-life material** | **kg** | **%** | **kg** | **%** |
| **Re-use and 1st grade recycling (circular)** | **76%** | | **82%** | |
| Magnetic steel | 1056 | 40% | 1018 | 34% |
| Mineral oil 1st grade (70%) | 363 | 14% | 405 | 14% |
| Copper 1st grade (95%) | 0 | 0% | 458 | 15% |
| Structural steel | 569 | 22% | 575 | 19% |
| **2nd grade recycling (non-circular)** | **17%** | | **11%** | |
| Aluminium | 273 | 10% | 93 | 3% |
| Mineral oil 2nd grade (30%) | 156 | 6% | 174 | 6% |
| Copper 2nd grade (5%) | 0 | 0% | 24 | 1% |
| Porcelain | 26 | 1% | 30 | 1% |
| **Incineration with energy recuperation** | **5%** | | **5%** | |
| Wood, paper, cardboard | 131 | 5% | 149 | 5% |
| **Land-fill disposal** | **2%** | | **2%** | |
| Other parts (kg) | 53 | 2% | 60 | 2% |
| **Total weight (kg)** | **2627** | **100%** | **2986** | **100%** |

**TABLE 2 – DEGREE OF CIRCULARITY OF THE MATERIALS OF A TYPICAL DISTRIBUTION TRANSFORER (ESTIMATED)**

Using copper as the conductor material for the high voltage winding increases the proportion of material entering an entirely circular process from 76% to 82%.

## MATERIAL RECYCLING FROM CAST-RESIN DRY TYPE TRANSFORMERS


**FIGURE 4 – CAST-RESIN DRY TYPE TRANSFORMER** (SOURCE: DEUTSCHES MUSEUM, LICENSED UNDER CREATIVE COMMONS CC BY-SA 3.0)

Cast-resin dry type transformers pose a major difficulty for recycling. The windings, which in the case of oil filled transformers can be extracted easily and recycled, are entirely overmoulded with an epoxy or quartz resin. Separating this resin from the metal coils takes time and energy and is not economically viable within the EU. It would require powerful machines for pre-cutting the material into smaller pieces (typically 1000 kN) and several rounds of milling and grinding with high-powered shredders (typically 4500 kN). Even then, the metal can only be recovered at low purity (<95%) for use only in secondary applications. Moreover, more than 80% of dry type transformers use aluminium as a winding material rather than copper, which limits the scrap's economic value. If separation were possible, the economically worthless resin parts would still make up about 40 - 50% of the material weight in the case of aluminium windings, and 30 - 40% of the material weight in the case of copper windings. Since the resins are chemically diverse and recycling is highly complex, they cannot be recovered and have to be disposed in landfill.

These findings are supported in an Italian University thesis [2, p.85-86] which states that full separation between resin and coil is today "highly cost and time consuming and economic nonsense". Even the specialized cryo-grinding process is not seen as a solution according to the thesis, since it would require an excessive quantity of liquid nitrogen for the separation (120 litres of liquid nitrogen to recover 300 kg of resin).

As a result, the coils still entirely covered with cast resin are sold together with other electromechanical scrap for export outside the EU. It is assumed that most ends up in India, where a low-paid workforce separates the resin from the metal coils in semi-automated processes. The recovered metal is sold to foundries as low-grade scrap, with the remainder ending up in landfill.

Other parts of cast-resin dry type transformers, including the magnetic steel in the core, structural steel parts in the frame, and ceramic components, follow the same recycling path as in the case of liquid-filled transformers.

## Material recycling from open dry type transformers

There is also no favourable business case for recycling open dry type transformers, such as vacuum impregnated types. Compared with cast-resin dry type transformers, there is no complex separation of resins from conductor material, but there are other issues. About 15% of the coil weight represents materials that were impregnated into the coil, such as plastics and glass fibres. These must be removed in a complex mechanical process and end up in landfill. After separation, the purity of the recovered metal is still low (<95%), which means that it can only be sold as second-grade scrap with low economic value.

Most dry type transformers use aluminium rather than copper as a winding material, which further limits the scrap value. As a result of all this, the economic value of the recuperated parts is very low compared to the time, energy and financial investment needed for their recovery.

# KEY FACTS

1. Liquid-filled medium-power transformers have a high degree of circularity at end-of-life. About 75% of the material can enter an entirely circular process, either re-used for a similar application or recycled into the same material (1$^{st}$ degree recycling). Almost 100% of the metals are recovered for either 1$^{st}$ degree or 2$^{nd}$ degree recycling.

    - Mineral oil can be recovered for re-use in transformers. In principle, nearly all the oil can follow this circular route. In practice, about 70% of the oil is recycled for re-use, and the remainder is re-used as second-grade oil in other applications.

    - Recovered aluminium does not reach purity levels higher than 98%. It is downgraded for use in second life products for which this purity level is sufficient.

    - Magnetic steel laminates can be cleaned and re-used in new, smaller transformers. However, the transformers currently being taken out of service have laminate thicknesses too great for the prevailing Ecodesign regulation. Some of this magnetic steel goes to be stamped out into laminates in Asian countries where low voltage transformers are not subject to loss restrictions.

    - About 3 - 5% of the transformer consists of organic material such as wood, paper, or corrugated cardboard that goes to waste incineration plants with energy recovery.

    - Just 1 - 2% of the transformer material cannot be re-used, recycled or incinerated, and needs to be disposed in landfill.

2. The degree of circularity of a liquid-filled medium-power transformer can be increased by using copper instead of aluminium for the high voltage winding.

    - More than 90% of the recovered copper will be recycled at purity level 1A (more than 99.9% purity). It can be melted and used again in electrical applications, including transformer windings, without further purification. This means that it follows a truly circular route that is highly efficient in terms of cost, energy use and environmental impact.

3. Cast-resin dry type transformers pose a major difficulty to recycling, because the windings are overmoulded with resin. Separation is complex, energy consuming, and not economically viable within the EU. As a result, coils covered with cast resin are sold along with other electromechanical scrap for export outside the EU, where a low-paid workforce separates the resin from the metal coils in semi-automated processes.

    - About 30 - 50% of the coil weight consists of resins, which go to landfill after separation.

    - Even if the conductor material is separated from the resin in the most effective way possible, its purity level remains low, which means that it can only be sold to foundries as low-grade scrap with low economic value.

    - Most dry type transformers use aluminium as a winding material rather than copper, which further limits the scrap's economic value.

# ANNEX: INTERVIEWED STAKEHOLDER COMPANIES

The authors would like to thank the following participating companies:

## Distribution system operators (DSOs)

- e-distribuzione (Enel Distribuzione), Rome, Italy
- I-DE Redes Eléctricas Inteligentes (Iberdrola), Bilbao, Spain
- Westnetz, Dortmund, Germany

## Transformer service companies

- Maschinenfabrik Reinhausen, Regensburg, Germany

## Transformer oil recycling specialists

- A.G.R, Carreño, Spain
- Starke & Sohn, Niebüll, Germany

## Transformer Recycling companies

- Nickelhütte Aue GmbH, Aue, Germany
- THECO Thesing, Coesfeld, Germany
- Recotex, Dorsten, Germany
- EES Trafoexpert , Hamburg, Germany
- SK metals GmbH, Kleve, Germany
- Elotec TDZ, Molbergen, Germany
- Schrott Bosch, Deizisau, Germany
- AFESA Medio Ambiente, Derio, Spain
- Alberich, Castellbisbal, Spain
- A.G.R, Carreño, Spain
- VI.BI. Elettrorecuperi Srl, Piancogno, Italy
- Elettromeccanica Dorica sas, Ancona, Italy
- Aprochim (Groupe Chimirec), Grez-en-Bouère, France
- Miteco Kneževac, Belgrade, Serbia

# OTHER REFERENCES

[1] T&D Europe Position Paper, "Circular Economy: Contribution to material efficiency applied to transformers", July 2018

[2] Marco Gabriele Scevola, Angelo Baggini, *Trasformatori di potenza MT/BT: Analisi dell'impatto sul fine vita delle carateristiche costruttive in contesto di economia circolare*, Universitá di Pavia, 2020

[3] Venugopal Pillai, "CRGO Issues Still Haunt Transformer Industry", T&D India, October 2018

[4] Bruno De Wachter, "Maximizing Distribution Transformer Resource-efficiency", European Copper Institute, October 2021