Towards net zero emissions - The role of circularity in transformers

Krzysztof Kulasek, Hitachi ABB Power Grids
Edvin Lindgren, Hitachi ABB Power Grids
Elin Johansson, Hitachi ABB Power Grids
Mercedes Jul, Hitachi ABB Power Grids
Johanna Flood, Hitachi ABB Power Grids
Miguel Oliva, Hitachi ABB Power Grids

Introduction - Circular economy

What if economic growth and meeting the energy and resource demands of a growing world population do not come at the expense of our planet's well-being and limited resources?
Maintaining the growth of global consumption in the long-term would require more supplies than we have to our disposal, as stated by the United Nations Sustainable Development Goals, number 12: **Ensure sustainable consumption and production patterns** [1].

Moving away from the traditional linear value creation and adopting a circular mindset will facilitate continued economic growth. Circularity means that instead of using natural resources and raw materials into products that end up as waste, they can be reused to a larger extent.

Circularity in practice implies reducing waste to a minimum; reuse, recycle, or keep within the economy, wherever possible, the product components and materials at the end of its life, productively using them again and again, shifting from the linear economic model that has traditionally relied on large quantities of resources available (relatively affordable, easily accessible materials and energy).

This concept is known as the circular economy and is applicable at any level,

The philosophy of the circular economy is to reuse the materials and resource demands from alternative sources such as recycling facilities instead of using raw materials from natural resources

either individual, corporate, regional, or global. Its implementation requires a systematic approach, collaboration, and focus, merging sustainability with business development with the goal to minimize environmental impact while at the same time maximizing the value creation for society.

Such an economy is based on a few simple principles coming from products designed and optimized since their conception for disassembly, reuse, or recycle.

The impact of pioneering circularity solutions in the energy sector could be significant, and the different stakeholders need to come together to drive the change towards a more sustainable future. This should be a joint effort of the whole industry, with technologists, manufacturers, and users partnering to make it happen. Industry standards and evaluation criteria also need to match the changed priorities and factor societal responsibility into the equation, to include sustainable and circular value creation solutions.

The concept and toolbox are available for the industry to come together to set the standards to ensure sustainable development of the electricity grids, with products and applications conceived considering environment and sustainability from the earliest possible stage at the time they are conceived followed but also during their whole lifecycle: design, manufacture, purchasing, use, and end of life.

Circular economy and transformers

Transformers have been part of the electrical network from their early stages, intrinsic to the development of the grid. They allow transporting energy over long distances, from generation stations to users, in a very efficient way, and they are connecting and supporting the integration of new renewables sources into the system.

Transformers have achieved high levels of efficiency thanks to material and technology development. They also have a long lifespan of 30 - 40 years, and most of their materials can be recycled at the end of their lifetime, which already makes them a product fitting in many aspects into the circular economy concept.

The high value of some of those materials, such as copper and electrical steel, has favored their disposal and recycling or reuse, in many cases looking for an economic return more than because of the reasons of circularity.

In other cases, the disposal comes to address safety, health, and environment hazards making the cost recovery and ultimately recycling a secondary target, like in replacement programs for PCB-filled transformers where specific processes were developed for that purpose [2]:

- The core is subsequently disassembled, and the metal sheets are cleaned with hot solvent.
- The transformer coils are granulated to separate the copper from the paper winding. The paper shreds (left) are compacted and destroyed; the resulting copper scraps can be recycled.

There are other cases where transformers are recycled, not only based on financial and cost reasons but also to reduce environmental impact. A recent example is the Stena recycling and ABB Hitachi Power Grids case in Sweden where old transformers will be disposed reusing or recycling about 99% of the material, comprising 64% material recycling, 35% clean, low emissions efficient incineration for energy and the balance 1% as disposed waste [3].

The life extension of transformers is another alternative, based on life assessments that includes everything from maintenance operations to a complete remanufacturing, which may typically imply rewinding the transformer and reusing the core and tank, with a renewal of accessories [4]. Today, life extensions are included in asset management initiatives supported by digitalization, fleet, and asset management performance programs.

While a complete overhaul is a technically sound solution, it is typically implemented in cases where other limitations or constraints apply (dimensions at the site, transport restrictions, or high associated cost). The reason behind this is that modern materials and design techniques allow a significant loss reduction (lower specific loss core material and new designs of windings and / or magnetic shunts), allowing a much-reduced cost of the losses favorably impacting the total cost of ownership.

It is possible to recycle up to 99 % of the old transformers with 64 % material recycling, 35 % clean, low emissions efficient incineration for energy and the balance of 1 % as disposed waste.

It is also typically less cost-efficient from the manufacturing perspective as it involves disassembling and reassembling an old transformer that is not typically fitting modern and efficient manufacturing practices.

In summary, circularity is present already in the transformers industry, with companies taking care of the transformer disposal and materials recycling, motivated by safety and environmental reasons (disposal of mineral oil and oil-impregnated materials, PCBs) but also to recover some costs coming from the residual value of copper and electrical steel. But considering that **almost 99 % of the transformer materials could be reused or recycled**, a lot more can be done towards circularity.

Transformer users and manufacturers can still make choices to influence and reduce the environmental impact during the whole life cycle starting from the design, the sourcing of materials, manufacturing, and transportation. With changing regulations and increasing resource consumption, those choices are likely to have an increased financial impact over the life of the product.

With that, business leaders can connect more and more and develop long-term strategies to include the circular economy models [5] since the process of changing any infrastructure is complex and needs time, like it is the case for transformers which are part of the large and interconnected grid systems, so starting as soon as possible will bring results sooner.

This paper will cover some transformer sustainability aspects and different options to move further towards circularity, with the following questions guiding the analysis:

1. What and where is the largest environmental impact driver?
2. What changes can we make to reduce environmental impact?
3. How can circularity be systematically considered in the whole transformers value chain to make it one step more of their lifecycle?
4. How do we make the change happen?

The life extension of transformers is another approach to the circular economy, which may typically include rewinding and reusing the core and tank, with a renewal of accessories

Life cycle assessments and transformer losses to reduce carbon emissions

The life cycle assessment (LCA) is a methodology to analyze the environmental impact of products considering all the stages of their life cycle.

When applied to transformers, LCAs show that transformer operation, and specifically the losses, which is the major contributor to its environmental and carbon footprint [7].

The carbon emissions associated with transformer losses are also dependent on the energy mix, meaning that the higher the contribution of clean and renewable energy sources, the lower the environmental impact. Therefore, the decarbonization of the energy system and the reduction of the transformers' carbon footprint go hand in hand as more "green" electrons pass by.

But improving the transformer losses has a direct impact regardless of the energy mix. That direct reduction of the environmental impact is the philosophy behind the transformer energy efficiency regulations.

Transformers' energy-efficiency savings do not come at an additional cost as high-efficiency products are more cost-effective over their lifetime than low-efficiency units when applying the total cost of ownership (TCO) concept [6]. Higher capitalized cost of losses leads to lower losses and higher efficiency with the higher purchasing price paying back over the years.

Although known, it is not always considered that better efficiency also leads to less greenhouse gases (GHGs) emissions with more available energy that can be efficiently used.

Being in all the different steps along with the electrical system, more efficient transformers imply enormous savings of lost power, thus reducing the carbon footprint. As an example, in the European Union alone, with an estimated 4.5 million distribution transformers, they could avoid 38 TWh of electrical losses and 30 million tons of CO_2 emissions every year.

An example of that contribution is illustrated in the optimization of a typical 40 MVA unit to the same total cost of overwhip (TCO) but with lower losses, as shown in Table 1 (figures calculated using the European average energy mix).

Recycled and low-carbon materials make a difference

But losses, being the most important contributor, are not the only factor affecting transformers' carbon footprint. A transformer, in a nutshell, contains electrical steel, insulated copper or aluminum conductors, insulation, mineral oil or ester fluids, steel tanks, plus some auxiliary equipment (cooling equipment, steel parts, bolts, cabling, mechanical and digital accessories).

The extraction, production, and transportation of all those materials release GHGs further up in the supply chain. The emission factors of the different materials vary greatly depending on the source, how they are processed, and on the share of reused / recycled materials.

The following case has been prepared to illustrate the emissions and climate impact coming from the materials in transformers. As there are many different transformer ratings and types, we have normalized the total materials to a unit

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weight of 1 metric ton, using a typical material split:

- Electrical steel 30 - 40 %
- Copper conductor 10 - 15 %
- Insulation paper 3 - 5 %
- Mineral oil/Ester fluid 10 - 20 %
- Steel tanks 15 - 20 %
- Other 10 %

In the case of distribution transformers, aluminum may also be used, with different emission factors.

The range of the GHG emissions, measured in an equivalent weight of carbon dioxide (CO_2e) that we can typically expect from the materials of such normalized transformer, is shown in Table 2.

The example shows that the total equivalent CO_2 emissions from the materials are almost 2.5 tons for a normalized transformer of one ton, with most emissions (91 %) coming from the electrical steel, copper, and steel tanks.

Increased use of recycled materials and materials from low-carbon suppliers

The use of recycled materials and materials from suppliers with low-carbon emissions along the supply chain is one measure to reduce the environmental impact in transformers and also benefit from other positive effects since the use of less-virgin materials contributes to minimizing air pollution, land use, water use, deforestation, biodiversity loss, and landfill. The extraction of virgin metals also requires more energy than recycling.

- **Tanks and other steel parts (nonelectrical steel)**
  Steel production is one of the highest carbon-dioxide-emitting industries with still no fossil-free steel produc-

Table 1. Example of design optimization

40 MVA 112 / 10.5 kV		Eco-efficient design	Standard
No load losses	(kW)	10.5	14.7
Load losses	(kW)	103	128
Peak efficiency index*	(%)	99.836	99.783
Initial purchase price	(€)	532 500	479 000
Total cost of ownership (TCO)	(€)	718 900	718 900
Total mass	(kg)	68 000	56 000
Operation time / lifetime	(yrs.)	35	
Capacity utilization	(%)	50	
Generation mix		Europe	

Impact	Value
Energy savings / year	91 542 kWh
Energy savings total	3 203 970 kWh
GHG emissions reduction (CO_2e / year)	38 112 kg
Total GHG emissions reduction (CO_2e)	1 334 000 kg

Table 2. The range of the GHG emissions

Material	Weight (kg)	PG average emission factor* (kg CO_2e/kg)	GHG Emissions (t CO_2e)	Ratio of emissions from each material
Electrical steel	350	2.765	0.968	40 %
Copper	150	4.738	0.711	30 %
Paper	50	0.817	0.041	2 %
Mineral oil / ester fluid	150	1.209	0.181	7 %
Steel tanks	200	2.5	0.500	21 %
Other	100	0	0.000	0 %
	1000		2.401	

(*) In those figures, we have used the known average assumed emission factor from our products at Hitachi ABB Power Grids

In the EU alone, with approximately 4.5 million distribution transformers, switching to the low-loss transformers can potentially save up to 38 TWh of electrical energy which translates to 30 million tons of CO_2 emissions yearly

tion along with the world with some initiatives, like HYBRIT, to change that in the long run. HYBRIT aims to replace the fuel in traditional blast furnaces with hydrogen made from renewable energy powered electrolysis, and the ambition is to have fossil-free steel out on the market by 2035 [8].
On the other side, all metal parts can be recycled to nearly 100 %.
The radiators and other steel parts (such as the tank or conservator) are an example for transformers as they are scrapped for recycling at the end of their lifetime.
Looking at the example, an increase in the share of using recycled steel by 40 % would give a reduction of CO_2e from steel of 23 % with a total impact reduction of 5 % transformers carbon emissions associated with materials.

- **Copper**
  Copper is one of the most recycled materials, and it can be recycled over and over with no loss of properties and for that is requiring up to 80 – 90 % less energy than the primary production [9].
  Although the demand for copper is increasingly met by recycling, it is not enough, which is why the extraction and processing of virgin copper done in a responsible way implies the least possible environmental impact [10].
  Under the same philosophy that energy supply from renewable sources reduces the carbon footprint, companies may procure copper from recyclable sources, but that would require tracing and distinguishing the source.
  Additionally, transformer manufacturers can reduce the environmental impact from copper by putting high requirements on their suppliers' processes and energy use. By sourcing copper from low-carbon suppliers along the supply chain, the associated emissions may be reduced by 50 % compared to world average copper production.
  As an example, the European copper industry has developed and is advancing strategies to reduce its own carbon footprint. Through significant capital investments, the copper-producing industry has successfully reduced its CO_2 emissions by cutting its unit energy consumption by 60 % compared to 1990. Globally, similar investments in copper-based strategies could reduce the world's carbon footprint by 16 % by 2030. This means a 5.7-billion-ton reduction in CO_2 and a savings of $860 in energy costs each year [11].

- **Electrical steel**
  The core material is also valuable, and in many cases, it is disposed to be reused in smaller size electrical machines (transformers, motors), contributing to circularity, but this is not typically tracked or accounted for.
  A systematic process to recycle core materials can be found in this case example by Hitachi [12] associated with amorphous core distribution transformers, where a closed-loop recycling process is described to turn the cores back into ferroboron, its main constituent material. The process involves checking in-use transformers to determine whether they can be repaired and, if not, dismantling the transformer and either reusing or recycling its core depending on its condition. The recycling route involves collaboration between users, trading companies, dismantlers, intermediate processing companies, and materials manufacturers.
  For the core steel, the same philosophy as commented for the copper about supplier requirements may be followed to reduce the environmental impact, which could also serve as an incentive for the industry to adopt additional measures to reduce the environmental impact.

- **Mineral oil**
  A straightforward example of circularity and reducing emissions is the use of recycled mineral oil.
  Even without the highest contribution to carbon emissions, this could be a simple step adopted to increase a circular mindset.
  In any case, re-refining mineral oil for reuse to avoid its utilization as a combustible would further reduce carbon emissions.

Using recycled materials for manufacturing of the transformer can further reduce their CO_2 footprint due to savings in mining, extraction, production, and transportation

In summary, even if circularity has been present in the transformer business associated with the materials, the associated benefits have not been made evident in many cases. A structured approach may help in that purpose, including accounting for those benefits in sustainability and / or life condition assessments reports and:

- Use of materials with higher secondary material recycled ratios
- Use of low carbon suppliers
- Processes for transformers disposal, recycling and / or reusing at the end of their lifecycle.

The example proposed shows the potential with the total greenhouse gas emissions from the materials being approximately 2.5 tons CO_2e for a normalized transformer of one metric ton.

The emissions associated with transformer material could be reduced by approximately 10 %, with a 40 % increased use of recycled steel and sourcing 40 % of the copper from low-carbon suppliers along the supply chain. If a larger share of the materials were from low-carbon sources, the emissions would be reduced even further.

Sustainability and transformer environmental footprint into the purchase evaluation

Transformers suppliers must meet strict requirements for transformer performance and fit for an application. Those are listed in contractual documents, including a specification, a list of applicable standards, and tests. In the bidding and purchasing process, offers are being evaluated on a competitive basis using different combinations of a decision matrix.

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These have been developed over the years and are considered as important elements: price, product performance, supplier qualifications, and quality data.

Sustainability is recently finding its way and being added to the evaluation, helping users to communicate sustainability goals and suppliers to understand the impact they have.

The economic evaluation typically includes the capitalized cost of losses, which drives design optimization focused on finding an optimum between the cost (material and labor) and performance represented by losses.

But losses are not the only choice available. A non-exhaustive list, indicating what else can be done additionally towards the circularity of transformers, is provided below to give a sense of the type of considerations that may include sustainability in the purchase evaluation.

- **From suppliers:**
  - Where are they sourcing the raw materials from? Responsible sourcing.
  - Sourcing materials produced with a more sustainable energy mix.
  - What are their operations carbon footprints like, do they have energy efficiency programs?
  - Mix of secondary and primary raw materials, use of recycled materials. Traceability from the origin.
  - In the case of cellulose-based insulation, where is the cellulose sourced from, and are deforestation, sustainable foresting, and is biodiversity taken into account?
  - Location considerations to minimize logistics and associated emissions.

- **Design:**
  Evaluation criteria and design considering TOC and LCA as input parameters:
  - Reduced losses, loss capitalization.
  - Easy to manufacture, design for manufacturing.
    - Selection of a design that requires less processing during manufacturing.
  - Design for recycling at the product development stage.
    - Reusability of materials, easy disposal.
    - Sustainable materials, avoidance of non-recyclable materials.
  - Environmentally friendly carbon footprint materials.
  - Dry technologies and biodegradable liquids from natural and synthetic esters.
  - Safety by design concepts, to reduce the risk of failures (i.e., tank rupture mitigation).

- **Manufacturing:**
  - Optimized operations, reducing carbon footprint.
  - Renewable energy, fossil free electricity sources.

- **Transportation:**
  - Optimization of transport and logistics arrangements, from sourcing and product delivery.
  - Selection of sourcing closer to utilization. Supplying the transformer factory closest to the installation

point to minimize transport impact and risks.

- **Service life:**
  - o Energy efficiency programs.
  - o Preventive maintenance:
    - ▪ Transformer maintenance and other operative considerations to optimize the transformer life also have an influence (i.e., preventing catastrophic failures to avoid environmental problems due to oil spills, tank rupture, and fires).
  - o Digitalization:
    - ▪ Digitalization contributes to those efforts with intelligent date drives to help users applying the condition base. The digitalization also helps to optimize daily transformer utilization by applying dynamic loading models and switch cooling equipment (fans) precisely depending on ambient and loading conditions.
  - o Life asset management programs, life optimization.

- **Disposal and recycling:**
  - o Disposal processes and regulations to favor transformer recycling and reuse of materials, including traceability.
  - o Industry agreement, proactive cooperation at the end of the lifecycle.

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Although not generalized, this is a practice where we may already find some cases. An example by Liander is presented below about how to incorporate sustainability in tenders with a weighted score in the range pf 20 – 40 % [13]:

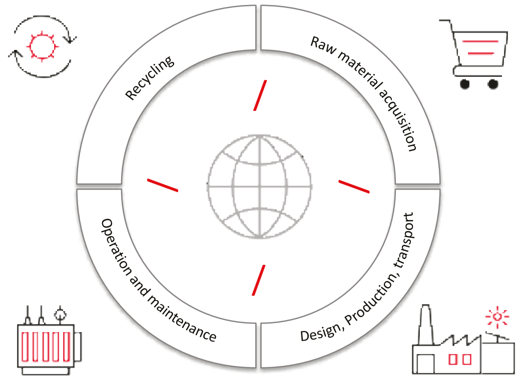
> “Liander purchases in an international, mainly European, market. Sustainable products and production are still in the early stages of development. Knowledge, standards, and legislation vary among countries. European rules, standards, and systems to support circular purchasing are not yet in place, except for the transformer market where the European Union Legislation 548 / 2014 sets the standards about the eco-design of new transformers. Since circular purchasing is still in its infancy, Liander chooses to have an open approach instead of selecting by specific measures / actions. This gives all vendors equal opportunities. Liander wants to start a change of mindset, e.g., the start of a common journey to make the asset and asset production chain more sustainable. To ensure that it will not be without obligations, all promises, agreements, and ambitions are audited and laid down in the contract. Depending on the product market combination, Liander gives substantial value to the sustainability scores. This can be in the range of 20 – 40 %. Where there is a good insight in market prices, Liander uses a maximum price. This way, the sustainability performance and ambitions can have a significant impact on the outcome of the tender.”

Circular economy in the transformer industry

Transformers life cycle

Transformers are ~90% recyclable
Disposal processes and regulations
Industry agreements

Energy efficiency programs
Preventive maintenance
Digitalization
Life asset management programs



Responsible sourcing
Production with a more sustainable energy mix
Carbon footprint reduction, energy efficiency programs
Mix of secondary and primary raw materials, use of recycled materials
Cellulose sourcing considering sustainable foresting and biodiversity
Location to minimize logistics

Evaluation criteria and design considering TOC and LCAs
Reduced Losses
Design for manufacturing and design for recycling
Reduced carbon footprint material
Dry technologies and biodegraadable liquids
Safety by design
Manufacturing with reduced environmental impact
Optimized operations, reducing carbon footprint
Renewable energy, fossil free electricity sourcing
Transportation
Optimization of transport and logistics
Selection of sourcing closer to utilization

There is an increased demand for reducing the environmental impact and greenhouse gas emissions in the marketplace, and circularity plays a big role in meeting those requirements.

Many companies are seeking collaboration across the value chain to cut greenhouse gas emissions and environmental impact from their supply chain by reducing the impact of materials and the use of products. Here is an example:

- Enel sustainability plan [14]: "The people centricity, a sustainable supply chain, sound governance, occupational health and safety, and a focus on the environment strengthen and complete the Group's sustainability strategy."
- National Grid's Environmental Sustainability Strategy [15]: "We are working with our supply chain to reduce the GHG emissions associated with everything they supply to us and encouraging them to adopt sustainable practices in sourcing and manufacturing. By 2020, 80 % of our top 250 suppliers will be reporting their emissions."
- Ørsted recently ranked as the most sustainable company in the world, targets carbon-neutral energy generation by 2025, and now sets out to work with its suppliers to decarbonize the supply chain by 2040 [16].

Pursuing circularity in transformers

Transformer energy efficiency regulations towards losses reduction and energy efficiency are one important effort towards sustainability as losses are the major contributor to the carbon footprint, but a lot more can be done to implement circularity in the energy industry and transformers in particular.

While manufacturers are striving towards developing circular solutions, the speed of change may be increased with a unified industry effort.

As the payback from the circular economy and sustainability will be seen and realized during transformer life, this requires good decisions and incentives today, such as evaluation criteria accounting for the associated benefits, for example, using an evaluation matrix with the weighted score assigned in the same way as the typical evaluation done today. When the evaluation system is shared and understood by suppliers, they can optimize their solutions and the whole value chain to meet customer expectations. This is used already by some companies with the inclusion of sustainability, early adopters that have started with 20 – 25 % already. The change will not happen over a short time, and there will be some learning required for the industry.

As an example, it would not be practical to ask for an LCA for a design at the quotation stage. However, using typical design data or simplified estimation will be valid at that stage. Working that way, the power sector can move towards reaching net-zero emissions.

Transformers technology and processes already contribute to that goal and can add more in the future, such as transformers manufactured with recycled copper and other materials, with much less carbon footprint, being measured and traceable.

This should be a joint effort of the industry, with the support of regulators, setting the rules of the game, manufacturers optimizing the full value chain, and users evaluating accordingly.

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