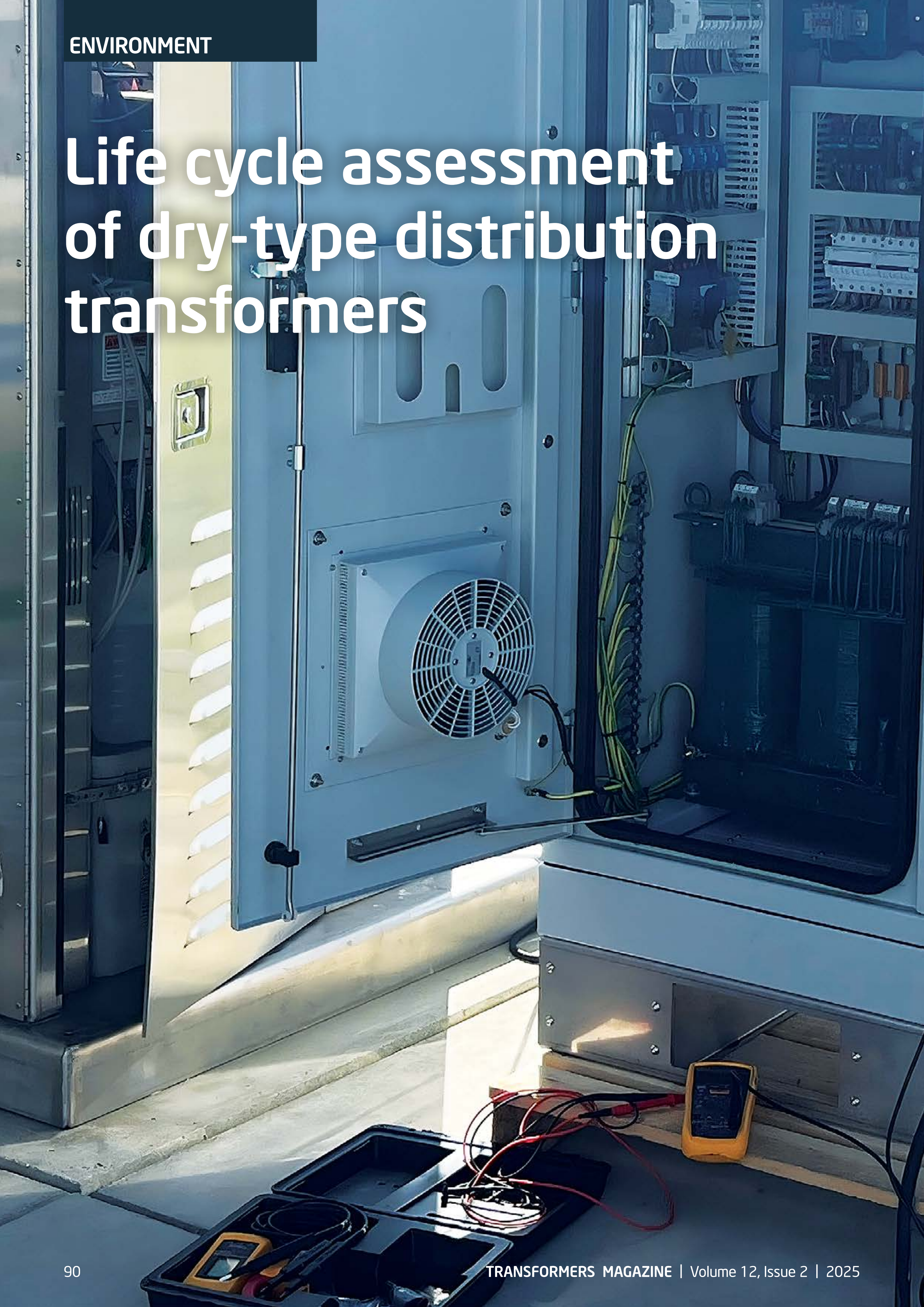
# Life cycle assessment of dry-type distribution transformers



Gaukhar Z. MAKASHOVA, Johannes M. M. BRUIJNEN, Stefan WESEMANN

## ABSTRACT

Transformers are an important component of the electricity sector, responsible for the transformation and distribution of electrical energy. Based on the life cycle assessment, this article evaluates the environmental impacts of a dry-type distribution transformer from the raw material acquisition to the end-of-life stages. The results show that the operation phase dominates in all environmental impact categories. In order to reduce the environmental impacts, it is suggested that the design of the transformers should be improved, renewable energy sources should be utilized during the manufacturing and operation stages, and the rate of the use of recycled components should be increased.

## KEYWORDS:

environmental impact, distribution transformers, dry-type transformers, life cycle assessment

> **Despite their importance in ensuring a stable and efficient energy supply, transformers are associated with various environmental impacts**

## 1. Introduction

The accelerating pace of industrialization and urbanization has increased the global demand for electricity. A central part of the infrastructure that supports this demand is transformers, which play a crucial role in the transmission and distribution of electrical energy, with an average energy efficiency ranging from 95 % up to 99.8 % [1]. The transformer is the key equipment of electrical networks, also playing a pivotal role in the decarbonization process. Despite their importance in ensuring a stable and efficient energy supply, transformers are associated with various environmental impacts [2].

Manufacturing transformers introduce a range of environmental impacts, including greenhouse gas emissions (GHG), resource depletion, and the generation of hazardous waste. During their operational lifespan, there are energy losses that generate direct emissions as well. Furthermore, the end of life of transformers presents additional environmental concerns, particularly regarding the separating epoxy resins from the coils, which requires additional energy. While the metal coils could be recycled, the resin elements ended up in the landfill, posing risks of soil and water contamination [3].

A transformer is a static electrical device that operates on the principle of electromagnetic induction to alter the voltage within an electrical system. Depending on its design, configuration, operational characteristics, and intended application, a transformer can either step up or down voltage and current levels without affecting the power or frequency of the electrical supply. Distribution transformers, typically positioned near consumer load centers, are commonly used as step-down transformers in power systems. Their primary function is to reduce high transmission voltages to safer, lower levels suitable for end-user consumption [1].

There are two types of transformers: dry-type and oil-immersed transformers. Both have their advantages and disadvantages. In this study, the environmental impacts of dry-type transformers were evaluated. Dry-type transformers are typically low-voltage transformers that are cooled by normal air ventilation instead of using liquids like mineral oil, common in other transformer types. Air and epoxy-based solid materials are used to meet insulation requirements. These solid insulations can withstand high temperatures without decomposing or releasing flammable gasses, further enhancing fire safety. This feature, including safety, minimizes environmental hazards associated with oil spills and leaks. Due to their non-flammable nature, dry-type transformers are used in solar and wind farms, important infrastructure facilities such as hospitals and data centers, and complex environments with potential fire hazards like chemical plants and mining operations [4]. Furthermore, the use of dry-type transformers is considered to be environmentally friendly since they do not contain oil or other hazardous substances [5]. Due to longer lifespans (up to 40 years for dry-type transformers) compared to other types (up to 30 years for oil immersed), frequent replacement is not necessary. This durability and longevity noticeably reduce electronic waste, making this type of transformer a conscious choice for sustainability [4].

> **LCA is a methodology for estimating the potential environmental impacts associated with a product or service considering the entire life cycle**

Considering that the distribution transformer is a critical component of the electrical grid and is responsible for the continuous supply of electricity, its construction should meet the efficiency, safety, and environmental performance criteria throughout its intended lifespan [1]. Although dry-type transformers play an important role in decarbonizing the electricity sector, there are still challenges regarding energy efficiency and associated emissions during the manufacturing and operation stages. Reducing the environmental impacts of the transformer industry contributes to the carbon emission reduction targets of the energy sector in general and is important for sustainability. At the moment, there are no studies on the environmental impact of the 15 kVA dry-type distribution transformers throughout their life cycle. Therefore, the aim of the study is to provide a detailed examination of the environmental impacts associated with dry-type distribution transformers using the Life Cycle Assessment (LCA) method. By critically assessing these impacts, the life-cycle stages with the largest environmental impacts are determined. This can be used to optimize the trade-off between using more material in the design of the transformers and lowering power losses during the operation stages.

## 2. What is Life Cycle Assessment?

LCA is a methodology for estimating the potential environmental impacts associated with a product or service considering the entire life cycle from the extraction of raw materials through the manufacturing, transportation, use, re-use, and maintenance of the product, and eventually recycling or disposal as waste at the end of life. LCA has the advantage of modeling the “carbon footprint” of renewable and conventional energy technologies. LCA is, therefore, the most suitable tool for evaluating the environmental impacts of products and identifying key areas where improvements could be made.

According to the ISO 14040 standards, the LCA method has four 4 main phases [6]:

- the goal and scope definition phase,
- the inventory analysis phase (Life Cycle Inventory-LCI),
- the impact assessment phase (Life Cycle Impact Assessment-LCIA),
- the interpretation phase.

**The goal of this study is to evaluate the potential environmental impacts of a 15 kVA dry-type distribution transformer through its whole life cycle using the LCA method**

During the first phase of the LCA, objectives, scope, and amount of data to be used in the analysis are defined. The second and most important phase is the Life Cycle Inventory Assessment (LCI), which implies an inventory of input/output data, which includes gathering data in order to fulfil the objectives of the analysis. The impact Assessment (LCIA) phase is the third phase of the LCA study, which provides additional information that helps estimate the impact of a product or system on the environment [7]. The last stage, or the stage of interpretation of LCA analysis, is the stage where the results of the phases are summarized and discussed in order to bring conclusions, assumptions and decisions according to the goal and scope of the study [1].

## 2.1. Goal of the study

The goal of this study is to evaluate the potential environmental impacts of a dry-type Distribution Transformer (DT) through its whole life cycle. A power distribution capacity of 15 kVA was chosen as a functional unit, and all raw materials, energy consumption, transportation, emissions, effluents, and waste disposal were based on this functional unit. The DT is set to be used to power the Alkaline Water Electrolysis for mobile hydrogen production.

The system boundaries are presented in Fig. 1, based on the steps of the DT manufacturing, use and end-of-life (EoL) processes. Boundaries were set using a cradle-to-grave approach, considering the processes from the extraction of raw materials to transformer utilization.

The following life cycle stages of the DT were modelled for the LCA

1. Manufacturing, including production of active parts, assembly of the active parts, Balance of Plant (BoP), final assembly with tests,
2. Transportation to the end user,
3. Operation phase,
4. EoL stage.

## 2.2. Life Cycle Inventory Analysis

The material selection and their weights used in the DT are part of the foreground process, while all other elements within the system boundary are background processes unless otherwise specified. The background processes were modelled using the Ecoinvent database [8]. The foreground data was collected by the author from the manufacturer and academic papers.

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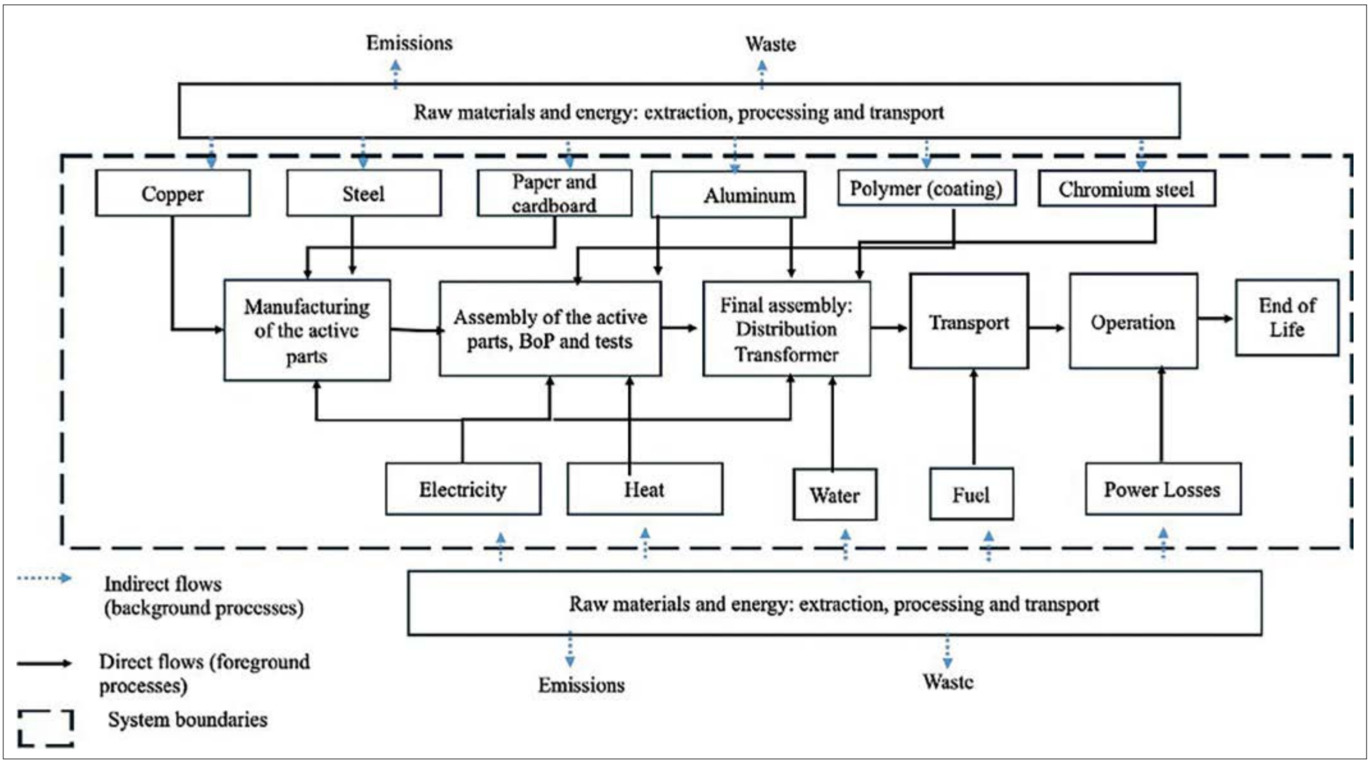

Figure 1. System boundaries of the DT

Table 1. Performance characteristics of DT

| Technical specification | Unit | Value |
|---|---|---|
| Rated power | kVA | 15 |
| Primary voltages | V | 3x380/400/415/440 |
| Secondary voltages | V | 3x480 |
| Percentage magnetizing current | % | 5 |
| No-load losses | W | 145 |
| Short circuit impedance at 75 °C | % | 3 |
| Total losses at 75 °C | W | 760 |
| Basic insulation level | kV | 3 |
| Efficiency level | % | 96 |
| Maximum temperature rise | K | 75 |
| Lifetime | Years | 40 |

**The material most used in the active parts and BoP is chromium steel, which is more than 50% of the total weight, while the second is the electrical steel**

Table 2. Life Cycle Inventory of 15 kVA DT manufacturing

| Name of the flow | Unit | Value |
|---|---|---|
| **Inputs** | | |
| Aluminium primary | Kg | 4,16 |
| Steel, chromium steel 18/8 hot rolled | Kg | 414 |
| Copper | Kg | 97,5 |
| Steel, electrical | Kg | 229,19 |
| Polyester (epoxy) resin | Kg | 10.5 |
| Polyamide | Kg | 2,9 |
| Electronics for control units | Kg | 0,9 |
| Brass | Kg | 0,16 |
| Polycarbonate | Kg | 1,6 |
| Carton for package | Kg | 0,4 |
| Others | Kg | 16,36 |
| **Total weight of built-in materials** | Kg | **775,34** |
| **Auxiliary inputs** | | |
| Electricity | kWh | 1440 |
| Heat | kWh | 1759 |
| Water | Kg | 600 |
| **Main outputs** | | |
| Waste paperboard | Kg | 0,4 |
| Polyester (epoxy) resin | kg | 0,007 |

Data for manufacturing processes was collected from Wesemann Projects BV transformer manufacturer company, located in Rotterdam (Netherlands). The company designs and manufactures high-end transformer solutions for the industrial installer and end-user [9]. Transformer inventory data related to manufacturing processes was collected through internal engineering reports (direct flows) and from the interviews. Indirect flow data such as extraction, processing, and transportation related to direct flows were obtained from the Ecoinvent database. Hand labor was out of the scope of this study due to difficulties in collecting these data and methodological assumptions. Moreover, it has an influence on input energy and environmental impact [10]. Performance characteristics for the DT are presented in Table 1. According to the DT type, a different number of materials is needed for the manufacturing process. The LCI data for input and output flows is shown in Table 2.

## Manufacturing of active parts, assembly, and BoP stage

Different types of materials were used to build the DT. The material most used in the active parts and BoP is chromium steel, which is more than 50% of the total weight.

The second metal is electrical steel, used mainly for solid cores. Copper used in the active parts (e.g., copper coils) represents 13 % of the total weight, and polyester (epoxy) resin used for coating is only 2 percent There are other materials contributing less than 1 percent to the total material weight such as electronics, plastics and cardboards as shown in Fig. 2. For modelling purposes, the origin of the material inputs for the manufacturing processes come from the Dutch and EU markets, and if not available then from the Global market.

### Energy for manufacturing of active parts, assembly, and BoP

The electricity supply and its assessment play an important role in the LCA. The choice of the source and the composition of the electricity mix can be highly influential factors in the environmental profile of a technology [11]. During the first stage of the life cycle, electricity originated from the Dutch grid mix (Fig. 3).

In 2023, a total of 120 billion kWh of electricity was produced in the Netherlands. The fossil fuel-based electricity supply was 58 billion kWh, which is about 48 per cent of the total supply. About 48 per cent of total electricity was produced with solar and wind energy and from biomass. Nuclear energy had a share of 3 per cent in total electricity supply [12]. The other energy sources (hydro and unspecified fossil fuels) were not considered in the LCA model as their share is only 2 per cent.

The auxiliary processes, such as manufacturing energy and water consumption for the DT, come from the statistical data and national reports [13-14] and were calculated according to the building parameters of the Wesemann BV factory. The calculated energy data was multiplied with the values from Fig. 3 and entered into openLCA software.

### Transportation stage

In the transportation stage, three important variables that drive carbon emissions from transportation need to be considered: distance travelled, mass transported, and mode used [15]. To evaluate the emissions during the transportation phase, the following variables were set:

- the distance from the manufacturer to the end user (within the Netherlands),
- the way of transportation (freight),
- the weight of the DT (775 kg).

> The choice of the source and the composition of the electricity mix can be highly influential factors in the environmental profile of a technology

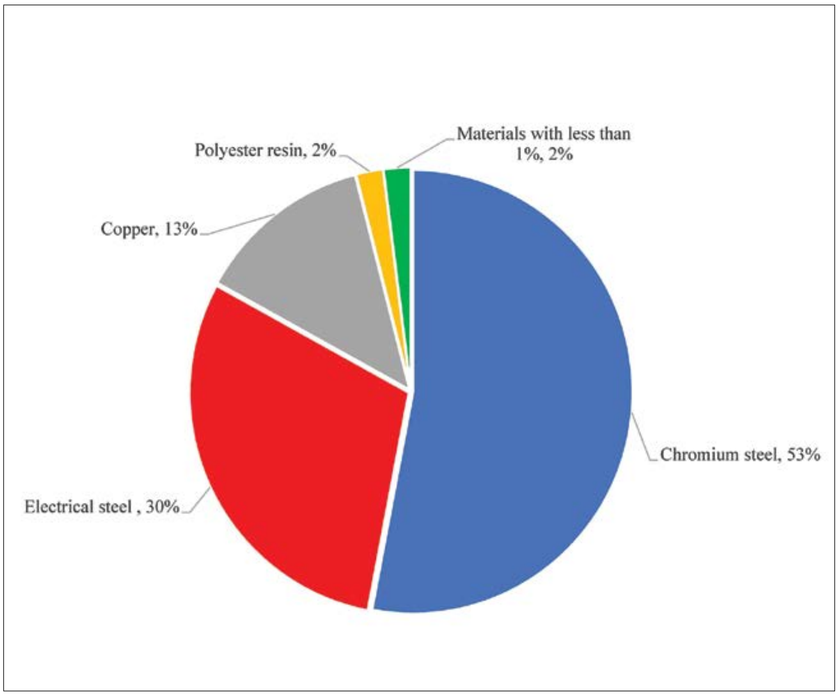

Figure 2. Materials used in DT

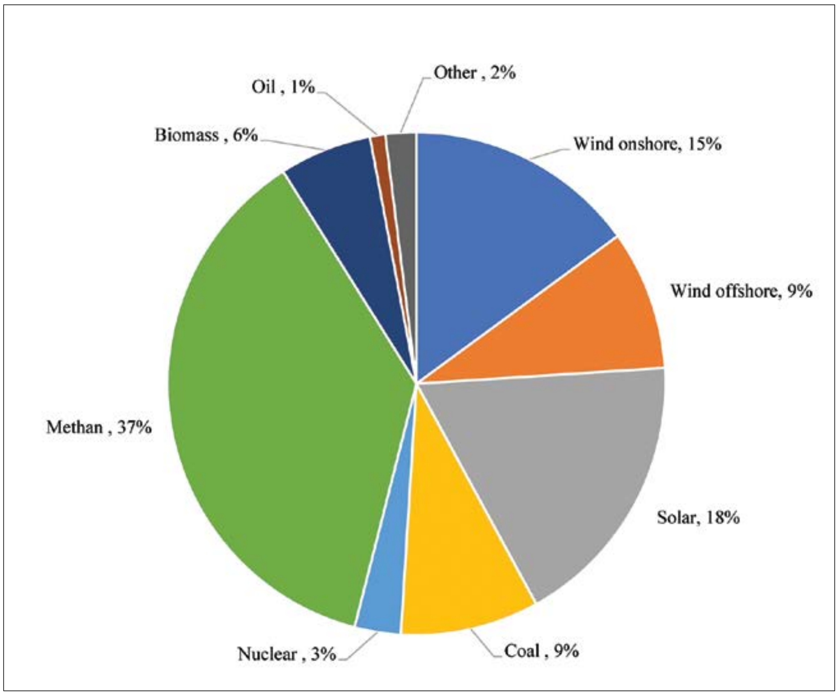

Figure 3. Electricity supply in the Netherlands in 2023 by sources [12].

### Operation stage

The load factor of the system is assumed to be 33% (116800 hours of operation), which is equal to an average of 8 hours per day for 365 days a year during the 40 year life cycle. Trans-

> **Transformer losses represent an important part of transformer use, and they have to be taken into consideration when calculating the environmental impact**

former losses represent an important part of transformer use, and they have to be taken into consideration when calculating the environmental impact. During the DT operation phase, the efficiency of dry-type transformers varies from 97 to 99 per cent [16]; therefore, total losses of 3 per cent were modelled. Total power losses are represented by the sum of load losses and no-load losses. Load losses are associated with the coils and depend on the transformer loading conditions. No load losses occur due to the magnetization current needed to energize the core of the transformer. No-load losses are constant and do not depend on the transformer load [17].

### End-of-life stage

Three potential EoL scenarios were considered in this study – recycling, disposal, and incineration. Materials presented in the Balance of plant (BoP), such as chromium steel, aluminum and copper, are fully recyclable [1].

Although the studied DT is a dry-type medium transformer, the absence of oil in its components poses a challenge for recycling such transformers. Due to the presence of epoxy resin in the windings, metals such as copper and electric steel are difficult to recover. Furthermore, epoxy resins are chemical compounds with complex structures and therefore, windings covered with resin require energy-intensive equipment to separate the resin. As a result, coils covered with epoxy resin are sold along with other electromechanical scrap for export outside the EU, where the separation of the resin from the metal coils would take place [3].

To evaluate the impacts during the EoL stage, the following materials from the DT were used for recycling:

- copper and brass used in BoP with a recycling rate of 90 percent. The recovered materials have the highest purity level 1A, meaning that they can be used again for electrical applications, including transformer windings, without further purification [3],

Table 3. LCIA results of the DT with the ILCD impact categories per 15 kVA (Eq - Equivalent).

| Impact category | Reference unit | Manufacture | Transport | Operation | End of Life | Result |
|---|---|---|---|---|---|---|
| Acidification (freshwater and terrestrial) | mol H+-Eq | 4.93E-05 | 2.49E-05 | 9.84E-03 | -2.42E-03 | 7.49E-03 |
| Carcinogenic effects | CTUh | 2.06E-08 | 5.05E-10 | 2.51E-07 | 6.13E-08 | 3.33E-07 |
| Climate change (GWP 100a) | kg CO2-Eq | 8.69E-03 | 5.28E-03 | 4.00E+00 | -2.92E-02 | 3.98E+00 |
| Freshwater ecotoxicity | CTUh.m3.yr | 4.34E-01 | 6.80E-02 | 6.11E+01 | 8.58E+01 | 1.47E+02 |
| Freshwater eutrophication | kg P-Eq | 3.34E-06 | 7.18E-07 | 9.40E-04 | 8.07E-06 | 9.52E-04 |
| Ionizing radiation (ecosystem) | mol N-Eq | 2.06E-09 | 5.86E-10 | 9.11E-07 | 4.25E-09 | 9.18E-07 |
| Ionizing radiation (human health) | kg U235-Eq | 6.60E-04 | 2.20E-04 | 3.87E-01 | 1.18E-03 | 3.89E-01 |
| Marine eutrophication (ecosystem) | kg N-Eq | 8.80E-06 | 8.41E-06 | 2.72E-03 | -1.21E-03 | 1.53E-03 |
| Ozone layer depletion | kg CFC-11-Eq | 1.46E-10 | 9.17E-11 | 1.41E-07 | -9.38E-10 | 1.40E-07 |
| Photochemical ozone creation | kg ethylene-Eq | 3.10E-05 | 3.38E-05 | 8.81E-03 | -3.74E-03 | 5.13E-03 |
| Resources depletion (mineral, fossils, and renewables) | kg Sb-Eq | 2.02E-08 | 2.98E-09 | 3.38E-06 | 5.18E-08 | 3.45E-06 |
| Respiratory effects, inorganics | kg PM2.5-Eq | 1.17E-05 | 2.86E-06 | 9.40E-04 | -1.91E-04 | 7.64E-04 |
| Terrestrial eutrophication (ecosystem) | mol N-Eq | 9.28E-05 | 9.03E-05 | 3.12E-02 | -1.47E-02 | 1.67E-02 |

- electric steel from the transformer coils and the chromium steel used for the BoP with 100 per cent recycling rate,
- electronic equipment from the control units and monitoring devices recycled at a rate of 22.3 per cent based on the global e-waste rate in 2022 [18].

> **Studied DT is a dry-type medium transformer, therefore, the absence of oil in its components poses a challenge for recycling such transformers**

The following components of the DT were disposed of (landfilled) [17]:

- epoxy resin molded coils,
- electronic waste from the control units that cannot be recovered.

Plastic components such as joints, buffers, and parts of the electronic unit, which cannot be recovered, were modelled as an incineration process.

## 3. Environmental impacts of the dry-type power transformers

The values for the environmental impacts of the DT in selected impact categories are presented in Table 3. These values represent the sum of impacts for all life cycle stages of the DT, i.e., raw materials extraction, manufacturing, transportation, and end-of-life processes. In this study, the ILCD 2011 methodology was chosen as an impact assessment method. ILCD 2011 recommends using midpoint impact categories as they focus on the analysis of the single environmental problems (e.g., climate change, acidification, etc.) while endpoint indicators show the environmental impact on three higher aggregation levels, such as the effect on human health, ecosystem, and resource scarcity [7].

> **Manufacturing accounts for a minor share (up to 15 per cent) of the total environmental impact, except for the carcinogenic effect in the DT studied**

A detailed analysis of the results of the LCA during the life stages (manufacture – transport – operation- EoL) is shown in Fig. 4. Manufacturing accounts for a minor share (up to 15 per cent) of the total environmental impact except for the carcinogenic effect in the DT studied. EoL has negative values in almost all impact categories due to the recycling of the steel, copper and aluminum as these materials are returned to the global metal reservoir, offsetting part of the manufacturing impact. However, the disposal of components that cannot be recovered (e.g., epoxy resin, electronic waste, and plastics) has a significant share in two impact categories – carcinogenic effect and freshwater

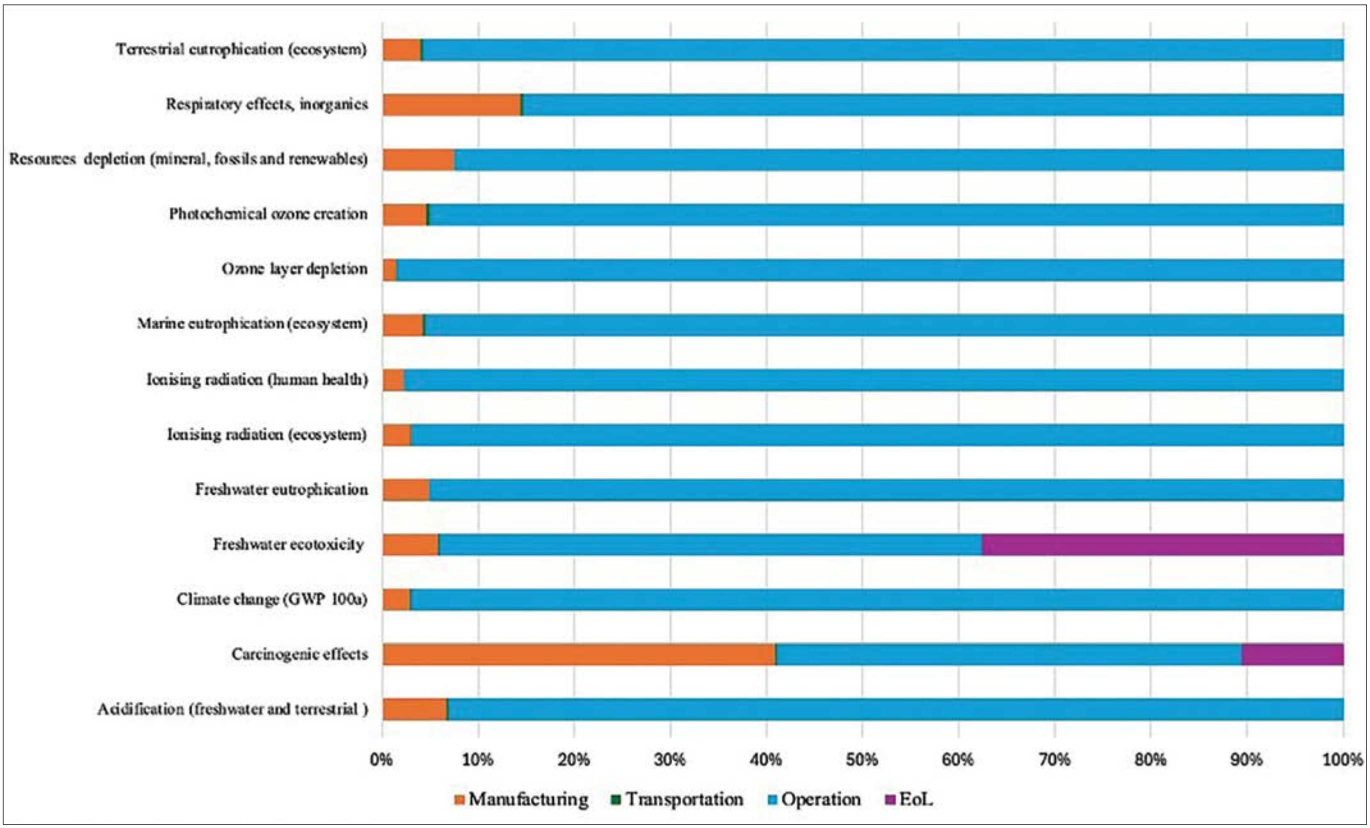

Figure 4. Environmental impacts of DT in life stages

> **The manufacturing and assembly phase of the transformers has a significant impact on carcinogenic effect and respiratory effect impact categories due to chromium steel**

ecotoxicity. Electronic products that were disposed of or incinerated impose a high risk on the environment, such as degradation and pollution of soil, contamination of water sources and release of toxic fumes (from e-waste combustion) [19].

The manufacturing and assembly phase of the transformers has a significant impact on carcinogenic effect and respiratory effect impact categories due to chromium steel in the BoP with a share from 53 up to 97 per cent. Copper is the second metal contributing to the high impact values, especially in freshwater ecotoxicity (Fig. 5). The production of copper and steel requires large amounts of fossil energy sources, which is the reason for the high contributions of these materials in the results.

The share of "other" in the category of ozone layer depletion (ODP) belongs to the origin of electricity. In the process of transformer manufacturing, the insulation modules need to be handled in a special insulation room where the drying process occurs. The high-temperature drying takes place in the vacuum ovens for about 4 hours, which requires a certain amount of energy. Therefore, electricity contributes about 30 per cent to the total impact.

The transportation stage has the lowest impact due to the small distance and the low weight of the DT. With the increase in transportation distance and for high-voltage, large-capacity transformers, the impact is higher, but such calculations were out of scope in this study.

The environmental impacts during the operational phase are largely influenced by the type of energy source used and the associated power losses. Renewable sources like wind or solar PV would have a lower environmental impact, reducing the overall footprint of energy use. As materials can be recycled but energy cannot, the impact of power losses becomes even more significant when non-renewable energy is used.

## 4. Limitations of the study

Considering the wide range of inputs used for this research, the following limitations are presented.

1. Matching processes from the inventories with the data available from the database used was possible for almost all modelled materials and processes. However, there were limitations. For example, thermoplastic used in the conductors is modeled as a polymer since it has similarities in the manufacturing process.
2. Concerning the end-of-life phase, available data on recycling processes for metals (e.g., stainless steel, copper, aluminum) is limited in the database. Therefore, the closest processes on recycling (e.g., aluminum scrap, reinforcement steel treatment) were used to assess the impacts from the EoL stage.
3. From a methodological perspective, the functional unit and boundaries should be set in LCA. In this study, the results are represented within cradle-to-grave system boundaries and the functional unit of 15 kVA capacity was established. Changing the functional unit or system boundaries would show different results.

## Conclusion and recommendations

An LCA was performed to analyze the environmental impacts of a dry-type distribution transformer. The results show that acquiring raw materials in the manufacturing process to produce chromium steel containing active components has a major impact on the carcinogenic and respiratory effects categories. To reduce the emissions from these metals, additional strategies should be implemented, such as putting high requirements on copper and steel suppliers' processes and energy

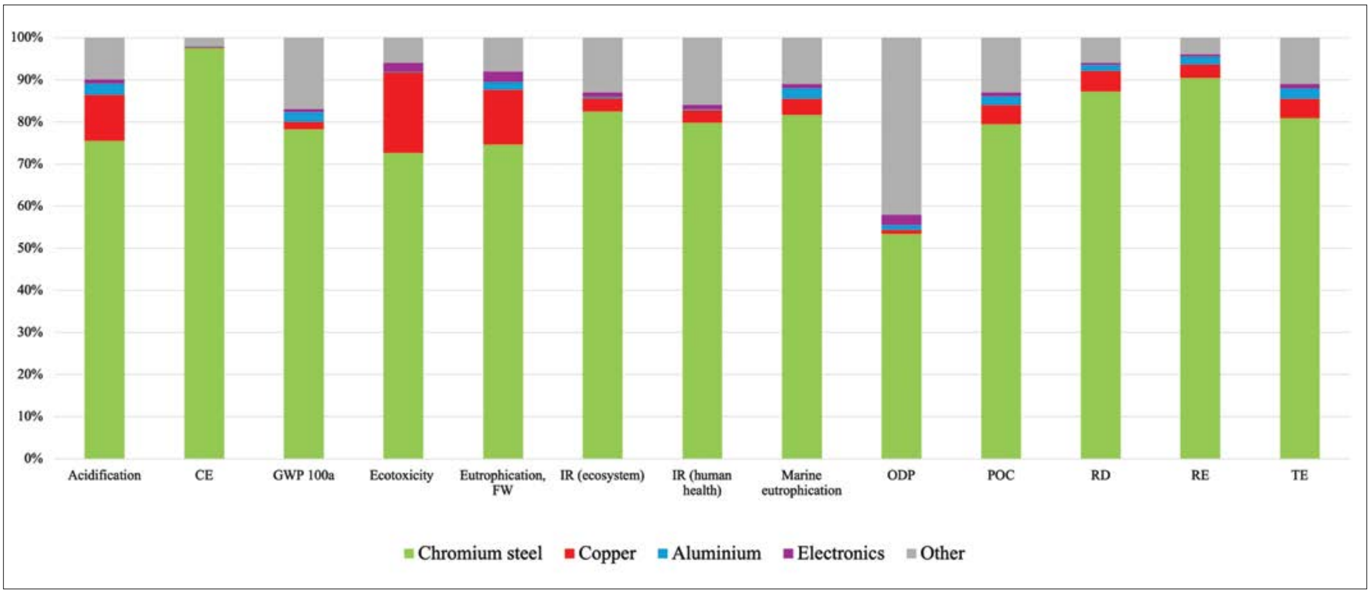

Figure 5. Contribution of the components in impact categories

consumption (e.g., increased share of recycled steel in new products, low-carbon suppliers, etc.). By sourcing copper from low-carbon suppliers, emissions could be reduced by as much as 50% compared to the global average for copper production. Relying even more on low-carbon materials would further decrease overall emissions [20]. Nevertheless, copper has a major impact on the following categories: acidification, freshwater ecotoxicity, freshwater eutrophication, photochemical ozone creation, resource depletion, and respiratory effects. The process of drying the insulation modules in the assembly stage consumes significant energy and contributes to the Ozone layer depletion impact category.

> **By sourcing copper from low-carbon suppliers, emissions could be reduced by as much as 50% compared to the global average for copper production**

Major impacts were shown to be related to the operational phase and the sources of the electricity, accounting for more than 90 per cent of all impact categories. It could be concluded that improvements in the environmental impacts could be achieved when using renewable energy sources. An analysis of transformers connected to renewable energy sources in Sweden showed that environmental impacts of the transformer's operational stage type could be easily and swiftly offset by enabling the integration of more renewable energy sources without the need for costly grid reinforcement measures [21]. To reduce load losses during the operation stage, improvements in design could be made. Creating a design that includes the substitution of highly environmentally intensive components for components with a lower carbon footprint is important in decreasing the impacts of this equipment. One of the solutions would be the use of amorphous metals in the transformer cores. Studies on the environmental assessment of transformers have shown that amorphous dry-type DTs are more sustainable solutions with respect to the Global Warming Potential impact category than conventional DTs based on copper or steel. Furthermore, using amorphous metal as core material allows a remarkable reduction of transformer losses by 50%-70%, reducing CO2 emissions [22]. Moreover, using recycled materials to manufacture the transformers can further reduce the environmental impacts due to decreased mining, extraction, production, and transportation activities.

Finally, the improvement strategies in EoL for electronic waste would increase the recycling rate and thereby potentially reduce the environmental impacts.

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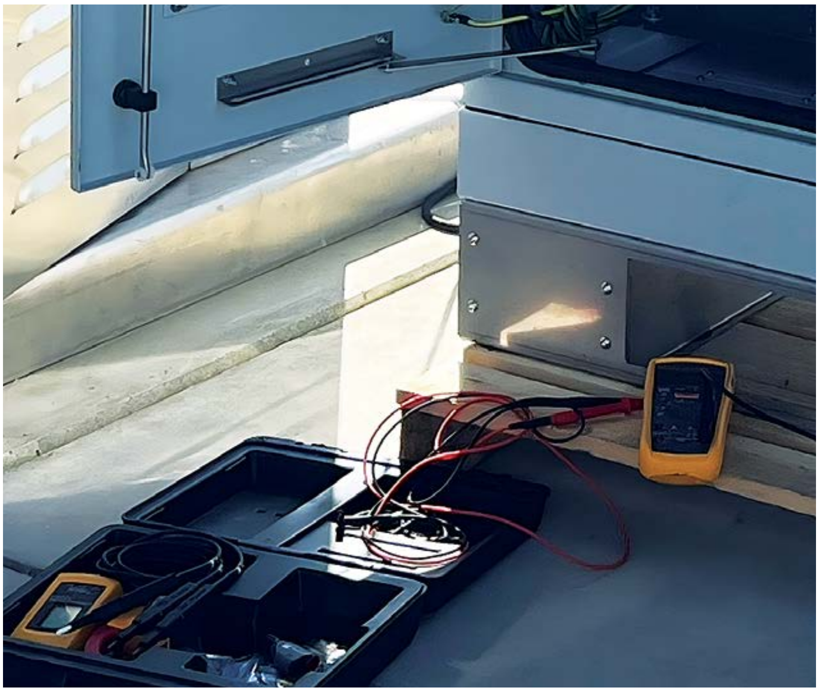

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## Authors

**Dr. Gaukhar Z. Makashova is an Environmental Consultant at INERC BV b**ased in Amsterdam. She holds an MSc. in Environmental Sciences and a PhD in Economics. She conducts research on assessing environmental impacts, including leading and executing research on applying circularity principles in the energy sector. She has more than 15 years of experience in consultancy. She has also co-authored e-learning courses on hydrogen safety within the ATEX framework.

**Johannes M. M. Bruijnen** is a Hydrogen and Explosion Safety Assurance Engineer. Currently working at INERC BV, he is Responsible for the implementation of Hydrogen Safety Engineering and Hydrogen as an Energy Carrier at the Naval Base in Den Helder and within the Dutch Naval Fleet. In this role, he developed and implemented the integrated mobile renewable hydrogen production system. In his current role, he supports HSE implementation plans for innovation projects within the Ministry of Defense. His current expertise has recently been broadened towards explosion safety and hydrogen safety.

**Stefan Wesemann** is the owner of Wesemann Projects BV, based in Rotterdam, South Holland, Netherlands. Wesemann projects produce transformers and complete power solutions for medical devices, marine applications, and the renewable energy market. Besides the production of transformers, standard uninterruptible power supplies are rebuilt for client-specific products. In the last few years, the company developed intelligent frequency/voltage converters and rectifiers.
In this way, Wesemann Projects designed, developed, and built the Green Energy Transformer to enable a steady power supply towards the Scalable Hydrogen Fuel Application of MRE.