TRANSFORMERS MAGAZINE'S
INDUSTRY NAVIGATOR

SUSTAINABILITY AND DIGITALIZATION

Green Material Alternatives for the Transformer Industry

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SCM Consulting GmbH
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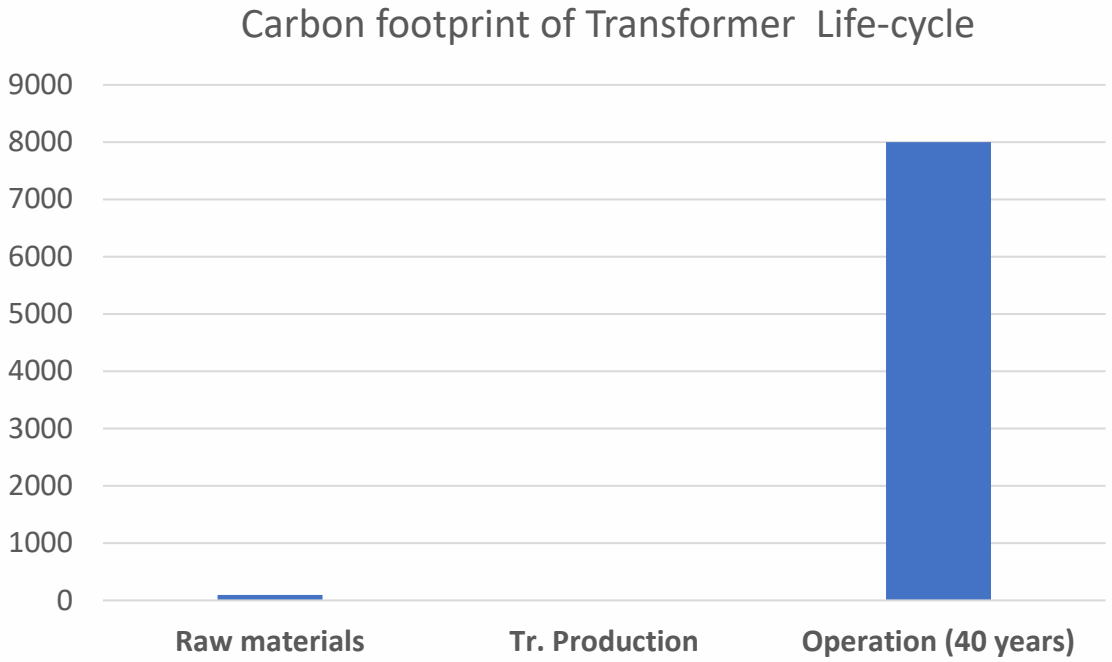
SCM Consulting

Transformer Life-cycle



Raw materials	Tr. Production	Operation (40 years)
100	2	8,000

- The figures are index values (raw materials assigned as 100) and are intended to show relative magnitudes
- Average load of transformer during operation is taken as 50%
- For transformer producers, raw materials are defined as Scope 3 and are usually not reported (Scope 3 reporting is voluntary)

Steel

Iron and steel industry accounts for 7.2% of global carbon emissions, which makes it one of the largest contributors in the world

Steel has the largest share of carbon emissions among the raw materials of a transformer (60 – 70%)

Transformer tank, conservator, and radiators are made of steel and the core is made of electrical steel.

1.0 ton of crude steel emits 2.0 tons of CO_2

Mining of iron ore and coal is the upstream industry for steel production

Steel industry is energy, capital, and technology intensive

All major steel companies have confirmed their 2030 and 2050 targets to eventually reach carbon-free status in 2050

There are several efforts to produce "green steel"

Methods to reduce carbon emissions in steel making

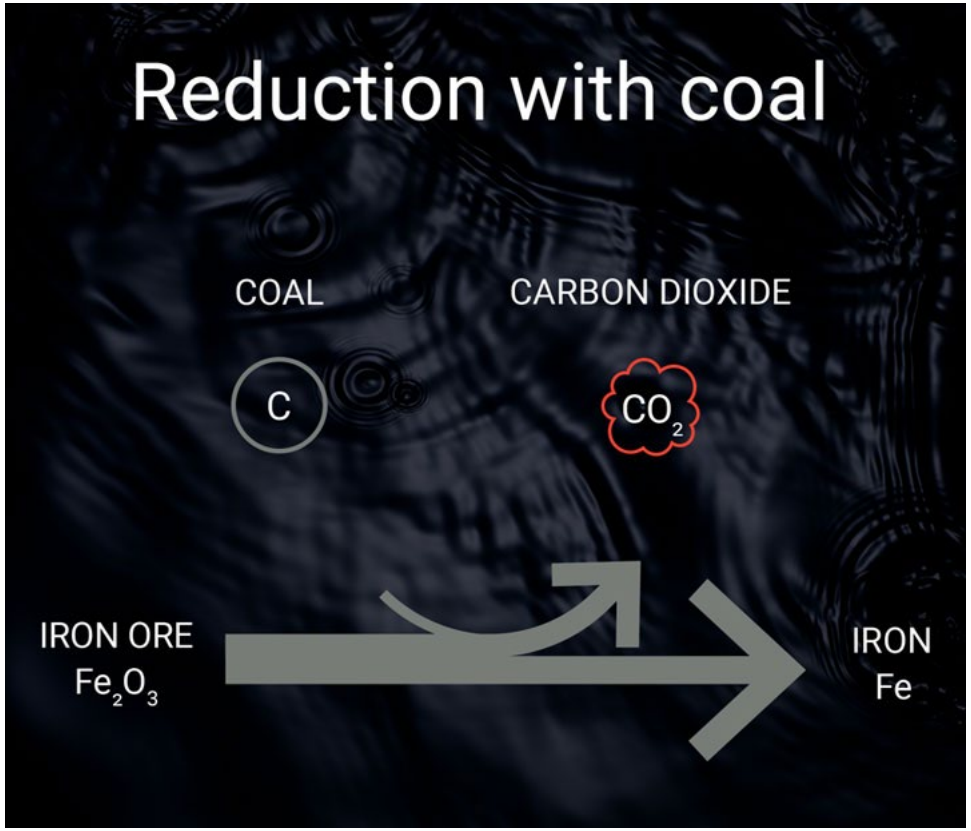
1. NO CHANGE TO THE MANUFACTURING PROCESS
- Rerouting
- Reallocation
- Carbon Capture And Utilization (CCU)
- Carbon Capture And Storage (CCS)

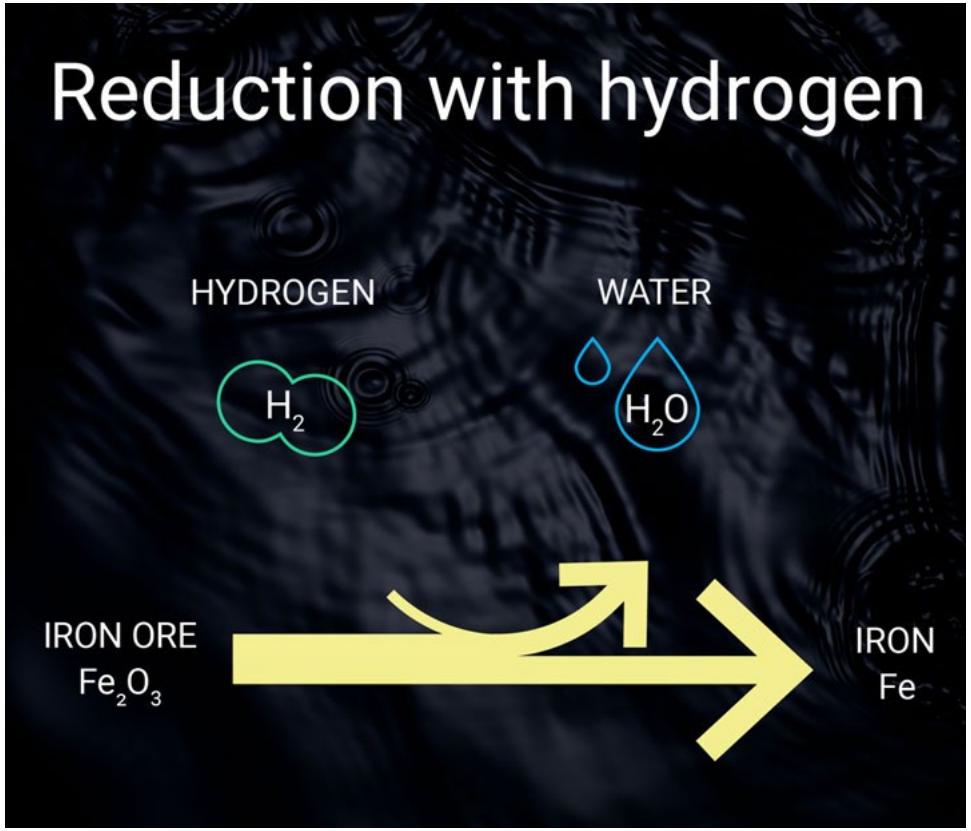
2. UPGRADING SCRAP-BASED STEELMAKING
- Low-Carbon Direct Reduction Iron (DRI)
- Green Electricity

3. UPGRADING IRON ORE-BASED STEELMAKING
- Biocoal
- Hydrogen Injection
- Top Gas Recycling (TGR)
- Submerged Arc Furnaces (SAF)

4. THE SHIFT IN TECHNOLOGY
- Fossil-Based Direct Reduction (DRI) with Electric Arc Furnaces (EAF)
- Fossil-Free Direct Reduction (DRI) with Electric Arc Furnace (EAF)

Conventional vs New Technology in Steelmaking

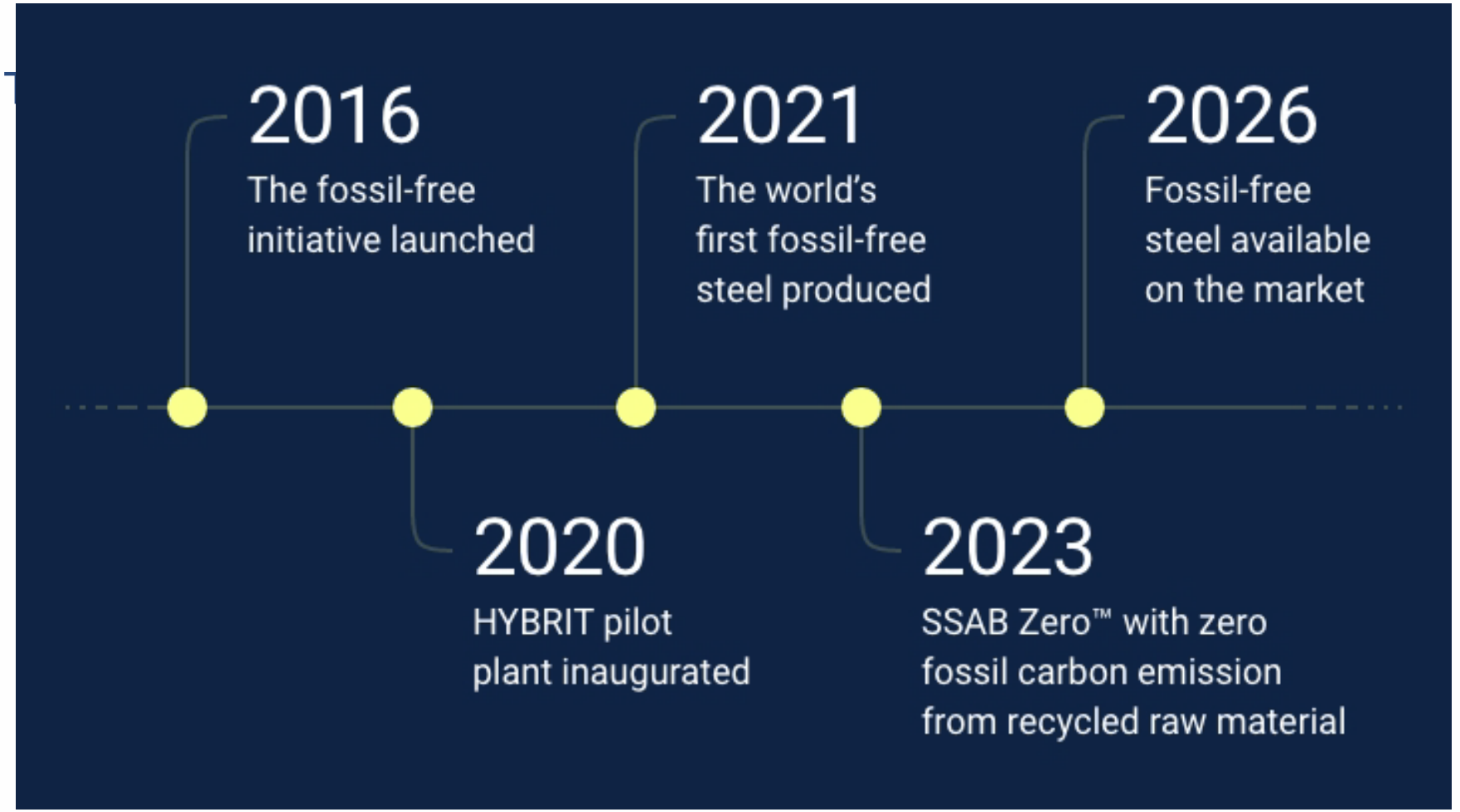




SSAB (Sweden) HYBRIT Project

- In 2016, SSAB, LKAB, and Vattenfall joined forces to create HYBRIT – a joint venture project that endeavours to revolutionize steel making. HYBRIT aims to replace coking coal, traditionally needed for ore-based steelmaking, with hydrogen, to achieve the world's first fossil-free steel-making technology, with virtually no carbon footprint.
- Development of hydrogen steelmaking using a newly built direct reduction plant (7,000 t/yr) in Lulea, with MEUR 150 investment
- Production plan: 1.3 million tons/year from 2026
- Volvo Group reveals the first vehicle made of fossil-free steel produced by SSAB, a load carrier for use in mining and quarrying (Oct. 13, 2021)
- SSAB is teaming up with Faurecia to jointly explore the development of fossil-free advanced high-strength steel for use in the automotive seating business. (September 2, 2021)
- Alfa Laval and SSAB join forces to produce the first heat exchanger made of fossil-free steel (May 31, 2022)
- SSAB ZeroỤ, made of recycled steel and produced with fossil-free electricity and biogas, is launched (2023)

SSAB (Sweden) HYBRIT Project



BAOWU

- On November 18th, 2021, the Global Low-Carbon Metallurgical Innovation (GLCMI) Alliance, initiated by China Baowu and co-sponsored by the global steel industry and ecosystem partners, was announced in Shanghai.
- The Global Low-Carbon Metallurgical Innovation Alliance is jointly established by 62 companies, universities, and scientific research institutions from 15 countries in the world. Its members include internationally renowned companies, such as ArcelorMittal, ThyssenKrupp, Tata, BHP, Rio Tinto, Vale, FMG, as well as scientific research institutes and engineering companies, including RWTH Aachen University, Ukrainian Metallurgical Research Institute, Danieli, and Pratt.
- The alliance positions itself as a technology exchange platform in the field of low-carbon metallurgical innovation to gather R&D resources of the global steel industry, upstream and downstream companies, universities and research institutions to collaborate in the development of basic, as well as forward-looking low-carbon metallurgical technology, with the goal of promoting technology cooperation, exchange and transformation, advancing the engineering and industrialization of low-carbon technologies, forming a low-carbon value innovation chain and promoting low-carbon transformation in the steel industry. Members of the alliance will follow the principles of openness, vision sharing, and intellectual property protection, actively respond to climate change, and work together for the future of the steel industry and for the benefit of mankind.
- Started research on the industrialization of hydrogen steelmaking using the existing 400 m3 test BF in Xinjiang.

Thyssen-Krupp

- Thyssen-Krupp has launched bluemint® steel with a reduced carbon footprint in 2022. It is also available for GOES grades from TKES and it is the first commercial GOES product with low carbon emissions

bluemint® pure

- Measure: use of HBI in the blast furnace, also hydrogen in the long run
- CO_2 reductions at the Duisburg production site and in a global context
- Allocated CO_2 reductions lead to reduced product-related carbon intensity
- CO_2 reduction of 1.5 tonnes of CO_2 per tonne of hot strip
- Residual carbon intensity of 0.6 tonnes of CO_2 per tonne of hot strip

bluemint® recycled

- Measure: use of scrap in the blast furnace
- CO_2 reductions at the Duisburg production site
- Balance-sheet CO_2-neutral recycling product
- CO_2 reduction of 1.35 tonnes of CO_2 per tonne of hot strip
- Specific CO_2 emissions of 0.75 tonnes of CO_2 per tonne of hot strip

Thyssen-Krupp

- Press release of 1 March 2023
- ThyssenKrupp Steel awards a contract to SMS group for a direct reduction plant: one of the world's largest industrial decarbonization projects gets underway
- ThyssenKrupp Steel places an order with SMS for the engineering, delivery, and construction of a hydrogen-powered direct reduction plant, two innovative melters, and the associated auxiliary units at the Duisburg location.
- One of the world's largest industrial decarbonization projects gets underway with an order volume for SMS alone of over 1.8 billion euros.
- Ground-breaking concept: direct reduction plant with Midrex technology, combined with two innovative melters, with a capacity of 2.5 million metric tons of directly reduced iron.
- The start-up is planned for the end of 2026.
- Significant step for industrial climate protection in Europe: annual savings of over 3.5 million metric tons of CO_2.

Arcelor-Mittal

- Development of hydrogen use in an existing commercial natural gas DRI plant (100,000 tons/year).
- ArcelorMittal has received a German state funding pledge for half the 110 million euros ($131 million) it plans to invest in a demonstration steel plant that will use hydrogen produced with renewable electricity.
- Environment Minister Svenja Schultze said Berlin would pay 55 million euros for the direct reduced iron (DRI) plant that will use green hydrogen to reduce iron ore in a CO_2-free steelmaking process, ArcelorMittal said in a statement on Tuesday.
- The company aims to produce "green" steel from 2025 onwards, obtaining it from clean DRI derived from a yet-to-be built 50-megawatt electrolyser, and melted with steel scrap in an electric arc furnace, which itself will be fuelled by green power.
- Uwe Braun, CEO of ArcelorMittal Hamburg, said the plant would enable his company to produce 100,000 tonnes of DRI for steelmaking with green hydrogen by 2025. FRANKFURT, Sept 7, 2021 (Reuters)

Arcelor-Mittal

(Eurometal.net, 20 Feb 2023)

- The European Commission has approved EUR 515 million ($549 million) as a part of the EU hydrogen strategy to help ArcelorMittal decarbonize its steel production in Spain and Germany
- Of the total grant, EUR 460 million will help ArcelorMittal to partially decarbonize its steel production in Gijón, northwest of Spain, where the company currently operates two blast furnaces.
- The Gijon steelworks' transformation will see the construction of a renewable hydrogen-based direct reduced iron (DRI) plant, which, together with a new electric arc furnace (EAF), would substitute old blast furnaces. Natural gas, initially used in the DRI unit, will be gradually replaced with renewable hydrogen and syngas generated from waste and metallurgical gases.
- The new facilities, which are likely to start coming online in late 2025, will produce 2.3 million mt/year of low-carbon DRI
- In October 2022, ArcelorMittal broke ground on its $1.3 billion transition to DRI-based steelmaking in Ontario, Canada

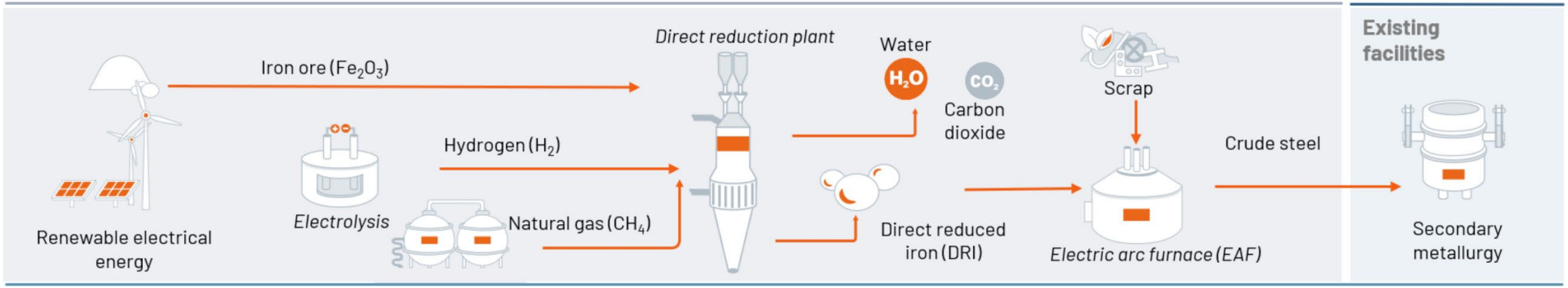
Salzgitter SALCOS®

13 July 2022 | Press release by Salzgitter AG

- Salzgitter AG's Supervisory Board approves funds of € 723 million for implementing the first stage of the SALCOS® - Salzgitter Low CO_2
- SALCOS® is aimed at converting the integrated steelworks into low-carbon crude steel production in three stages, over the period up until 2033. As part of the transformation, direct reduction plants and electric arc furnaces will be built and will then replace blast furnaces and converters in stages. The transformation will enable the process that was formerly based on coking coal to be replaced by a new hydrogen-based route. Emissions savings of around 95% a year are to be subsequently achieved, thereby avoiding approximately 1% of Germany's carbon emissions. (production launch: end of 2025)
- The new facilities will enable us to produce 1.9 million tons of green steel a year. Customers from a range of industries are already expressing keen interest. As a result, Salzgitter Group has already made arrangements for possible deliveries in recent weeks with customers from various sectors, including household appliance manufacturers, the automotive industry, and re-rollers.

SALCOS

Younited. Steelmaking. Reinvented.



Salzgitter SALCOS®

18 April 2023 | Press release by Salzgitter AG

- Salzgitter AG receives official notice of government funding for the SALCOS® low-CO_2 steel production program.
- As confirmed in this notice, the first development stage of SALCOS® will receive around € 700 million in federal funding and € 300 million from the state government. Combined with the company's own funds in excess of € 1 billion already approved by Salzgitter AG, financing is now assured for the first development stage of SALCOS®, which is due to be implemented by the end of 2025.

24 May 2023 | Press release by Salzgitter AG

- SALCOS® milestone reached – Salzgitter AG awards contract for direct reduction plant
- Salzgitter AG has contracted a consortium comprising Tenova, Danieli, and DSD Steel Group to build a direct reduction plant (DRP) on the site of Salzgitter Flachstahl GmbH.
- The plant will have a production capacity of more than 2 million tons of direct reduced iron (DRI) per year.

GravitHy

30 June 2022 | Press release

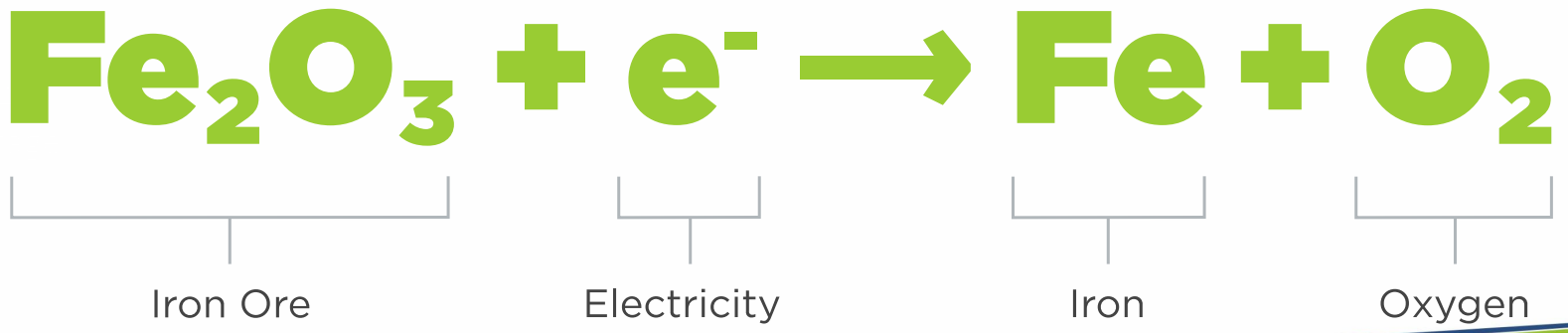
- On this date, the company composed of EIT InnoEnergy, the innovation engine for sustainable energy supported by the European Institute of Innovation & Technology, a body of the European Union (EU), Engie New Ventures, Plug, FORVIA, GROUPE IDEC through GROUPE IDEC INVEST INNOVATION, and Primetals Technologies, launch GravitHy – a future market leader in green iron.
- The project will build its first plant in the area of Fos sur Mer, Southern France, with construction commencing in 2024. The company aims for the plant to be fully operational by 2027, subject to the required regulatory approvals. GravitHy has an ambition to produce an annual throughput of 2 million tons of Direct Reduced Iron (DRI)
- The scheme will involve the installation of some 650 MW of electrolyser capacity, which will be one of Europe's largest by the time it comes on-line, to produce 110,000 tonnes of hydrogen per year

NSCarbolex™ Neutral by Nippon Steel C.

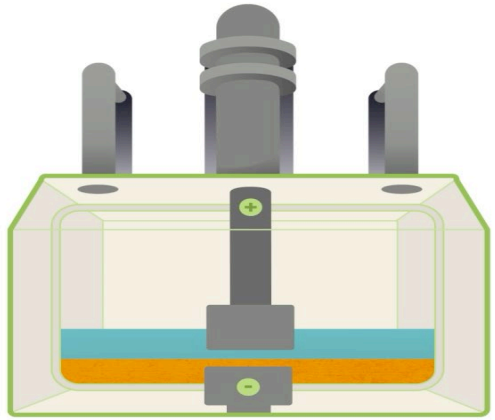
- Nippon Steel Corporation ("Nippon Steel") has launched the sales of "NSCarbolex™ Neutral," a steel product that is certified as reducing CO_2 emissions in the steelmaking process, in the first half of fiscal 2023.
- As a certification method of reducing CO_2 emissions, Nippon Steel is considering adopting a method (the mass balance method) in which the total amount of CO_2 emissions that Nippon Steel has actually reduced by reforming and improving manufacturing processes, etc., is determined and allocated to any given steel product.
- All steel products manufactured by Nippon Steel (including GOES) can be supplied as NSCarbolex™ Neutral, which makes it the second commercial GOES product with a low-carbon footprint in the market.
- Supply volume in fiscal 2023 is expected to be about 300,000 tons per year, calculated by basic unit conversion of steel products certified with virtually zero CO_2 emissions.

Molten Oxide Electrolysis (MOE) Technology from Boston Metal

- Boston Metal developed an electrolysis process that eliminates the need for coal in steel production. An electrochemical process, electrolysis uses direct electric current to separate chemical compounds into their constituent parts.
- In the cell, an inert anode is immersed in an electrolyte containing iron ore and then it's electrified. When the cell heats to 1600C, the electrons split the bonds in the iron ore.
- The result is a clean, high-purity liquid metal that can be sent directly to ladle metallurgy —no reheating required. The technology has the advantage of being modular and scalable.
- Semi-industrial validation of MOE cell for steel production (2022 – 2023)
- Demonstration plant deployment (2024 – 2025)
- Commercial plant deployment (2026 – 2010)



Molten Oxide Electrolysis



2050 Vision for Steel Industry - 1

Based on report from Wood MacKenzie (15 Sept. 2022)

- Decarbonising the steel and iron ore industry by 2050, in line with the Paris Climate Agreement, will require US$1.4 trillion of investment and revolution across every stage of the value chain.
- Wood Mackenzie's analysis shows US$800-900 billion will be essential to remove carbon from existing steelmaking infrastructure, such as setting up new hydrogen-based direct reduced iron (DRI) and electric arc furnaces.
- Mining companies will need to play an active role in cutting their operational emissions, as well as invest in new high-grade mines and green pellet capacities to feed green steel. In turn, this will require five times the current supply of high-grade pellet feed, an equivalent to 750 million tonnes, translating into an investment of US$250-300 billion
- Switching to clean energy will also require around 2,000 GWs of dedicated renewable generation capacity, equivalent to two-thirds of current global renewable generation capacity.
- A hydrogen ecosystem will also need to be developed for green steel, as decarbonisation will require around 50 million tonnes per annum of competitively priced green hydrogen, with commercial viability versus conventional steelmaking routes requiring green hydrogen supply at US$2/kg

2050 Vision for Steel Industry - 2

- The report warns that these measures will still fall short of emissions targets, necessitating an incremental US$200-250 billion investment in carbon offset measures, such as Carbon Capture, Utilisation and Storage (CCUS), as the industry will need to capture and store 470 million tonnes of carbon to reach its emission target in 2050.
- Green premiums are also inevitable, given that new technologies and low carbon feedstocks are likely to inflate steel production costs by 15–20%
- The transition to net zero calls for collaborative action globally and a unified approach across the value chain

Report by Hydrogen Europe

- Decarbonising the average primary steel plant in the EU would require 1.2–1.3 GW of renewables-powered electrolysers running at full load to produce enough green hydrogen to extract iron from iron ore
- The required Capex ranges from €3.3 bn to €7.0 bn for a single plant of average capacity. And that does not include the renewable energy that would be needed to power the electric arc furnaces that make the steel.

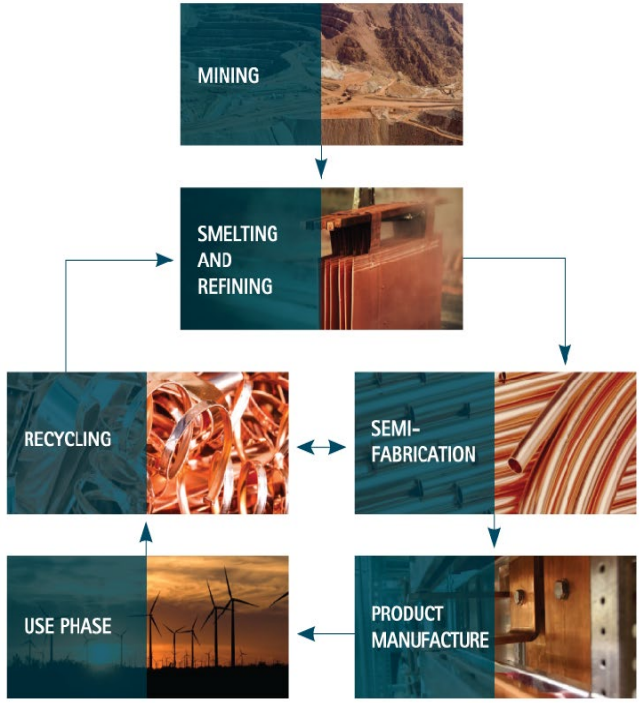
Steel - Conclusion

- Decarbonization of steel industry is a mammoth task with the following challenges:

1. Huge R&D investments needed: many aspects of the new steel making technology are not fully solved yet
2. Huge Capex is required for the implementation (government involvements will be needed)
3. Strong collaboration among stakeholders is necessary
4. Whole value-chain and logistics has to be re-established
5. The industry will face higher operating costs

- This transition is an ultra-marathon, and it will not follow a straight path
- However, there are already a few commercial offerings, and they will grow significantly after 2025
- Transformer industry could partner with green steel initiatives and start with the applications even today

Copper



- There is a long value-chain in copper conductors for the transformer industry
- Copper miners and smelters serve a wide range of industries, and transformers represent only a tiny portion of their portfolio. They are tier 2 and tier 3 suppliers to transformer industry and usually there is no direct business relation
- Copper has the second largest share of carbon emissions among the raw materials in a transformer (20 – 25%), after steel
- Copper mining emits 2.3–2.5 tonnes of carbon per tonne of metal, while smelting adds another 1.65 tonnes. In comparison, most of the fabrication processes have a much lower carbon footprint.
- There are also newer efforts to produce green copper

Green Copper from Boliden

- Boliden AB is a Swedish multinational metals, mining, and smelting company headquartered in Stockholm. The company produces zinc, copper, lead, nickel, silver, and gold, with operations in Sweden, Finland, Norway, and Ireland. Revenues: 6.3 BUSD (2021)

Low-Carbon Copper

- LESS THAN 1.5KG CO2EQ/KG COPPER
- Boliden's low-carbon copper is produced from copper mined in their own mines in the north of Sweden, using clean energy

Recycled Copper

- LESS THAN 1.5KG CO2EQ/KG COPPER
- The primary raw material for Boliden's recycled copper is used electronics. 100% recycled copper

Elcowire Group Low Carbon Copper / ASTA low carbon CTC

- Elcowire Group (Sweden) manufactures copper wire rods and further-processed aluminium and copper wire. The group is offering low-carbon copper, which is made possible through production that has undergone a substantial transformation due to electrification and automation of the various stages of the process. It has also been made possible by a very efficient ore concentration process and an energy mix including a high share of renewables. Elcowire is also offering a recycled version.
- The carbon emission value for Elcowire low carbon copper &recycled rod is 1.7 KG CO2EQ/KG Copper.
- ASTA is collaborating with Elcowire to produce low-carbon CTC for transformers.

Zero-emission Mining

- Komatsu announces collaborative customer alliance to advance zero-emission equipment solutions (August 2, 2021)
- Rio Tinto, BHP, and other mining firms have partnered with Komatsu manufacturing company to develop zero-emission mining equipment and infrastructure.
- The collaboration will form part of the Komatsu Greenhouse Gas (GHG) alliance, which also includes Codelco and Boliden as founding members.
- Members of the alliance will collaborate with Komatsu on the planning, development, testing and commissioning of the next generation of zero-emission mining.
- This alliance's initial work will aim to advance Komatsu's power-agnostic truck concept for a haulage vehicle.
- The vehicle will be designed to run on different power sources, including diesel-electric, electric, trolley (wired), battery power, and hydrogen fuel cells.

Aluminium

- Aluminium, in the form of foil or wire, is widely used in distribution transformers
- Aluminium has the highest CO_2 emission ratio among all transformer materials. 1 ton of primary aluminium emits 16 tons of CO_2 and, out of this, 80% comes from the electrolysis process, which is very energy intensive. Different forms of Aluminium products emit 18–20 tons of CO_2

- Hydro offers 2 new "greener" aluminium products

1. Hydro CIRCAL recycled aluminium: produced with a minimum 75% recycled aluminium and 2.3 MT of CO_2 per ton of product is guaranteed
2. Hydro REDUXA low-carbon aluminium: uses renewable energy in production and has a carbon footprint of 4.0 ton per ton of product

Insulating Oil

- Oil accounts for typically 10–15% of carbon emissions linked to raw materials in a transformer
- 1 ton of mineral oil emits 1.21 tons of CO_2
- Mineral oil is not biodegradable, and it is inflammable. Other than carbon footprint, mineral oil imposes environmental risks like fire or contamination through leaks or spillage
- There is already a wide range of alternatives to mineral oil, which are biodegradable
- Cargill - FR3: Biodegradable soybean oil

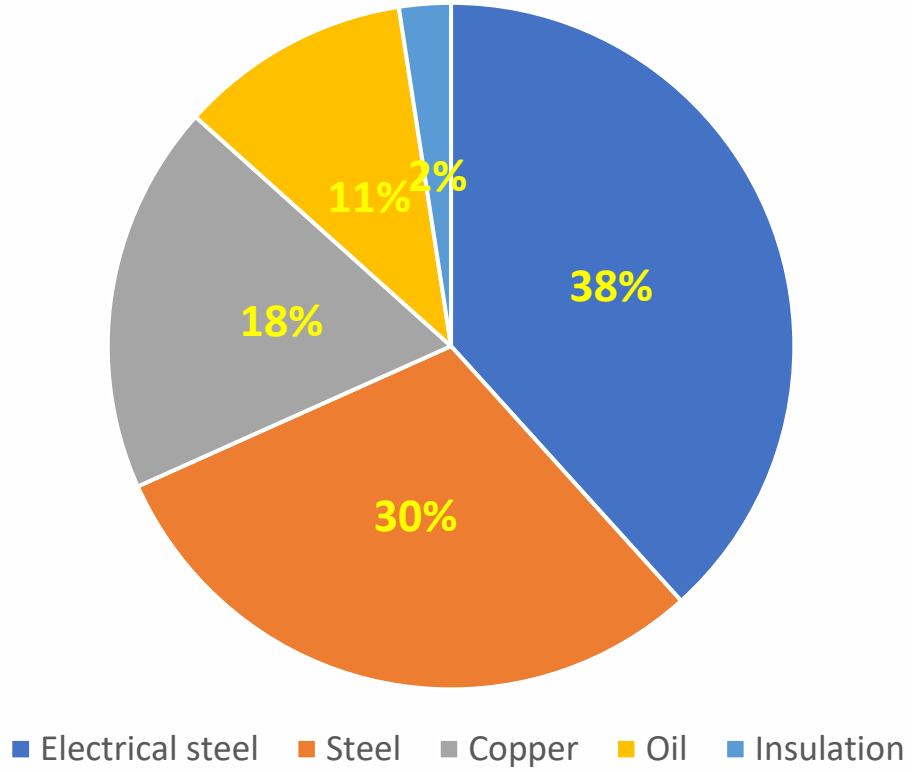
  Envirotemp 360 Fluid: Synthetic ester transformer oil
- M&I - Midel 7131: Synthetic ester fluids

  Midel eN: Natural ester fluid in 2 versions (from soybean and rapeseed/canola oil)
- Nynas - Nytro Bio 300X: Bio-based transformer fluid
- Ergon – HyVolt NE: renewable soy vegetable oil based ester fluid
- 2020–2024 HyVolt SE: synthetic ester fluid
- Shell . Diala S5 BD: biodegradable oil

Another alternative product is re-cycled oil, which has a much lower carbon footprint. Until recently, this was only available from smaller companies in limited quantities. Recently (Aug. 31, 2022), Nynas has launched NYTRO® RR 900X, which is a recycled product
Hydrogen-based reduction and smelting trials

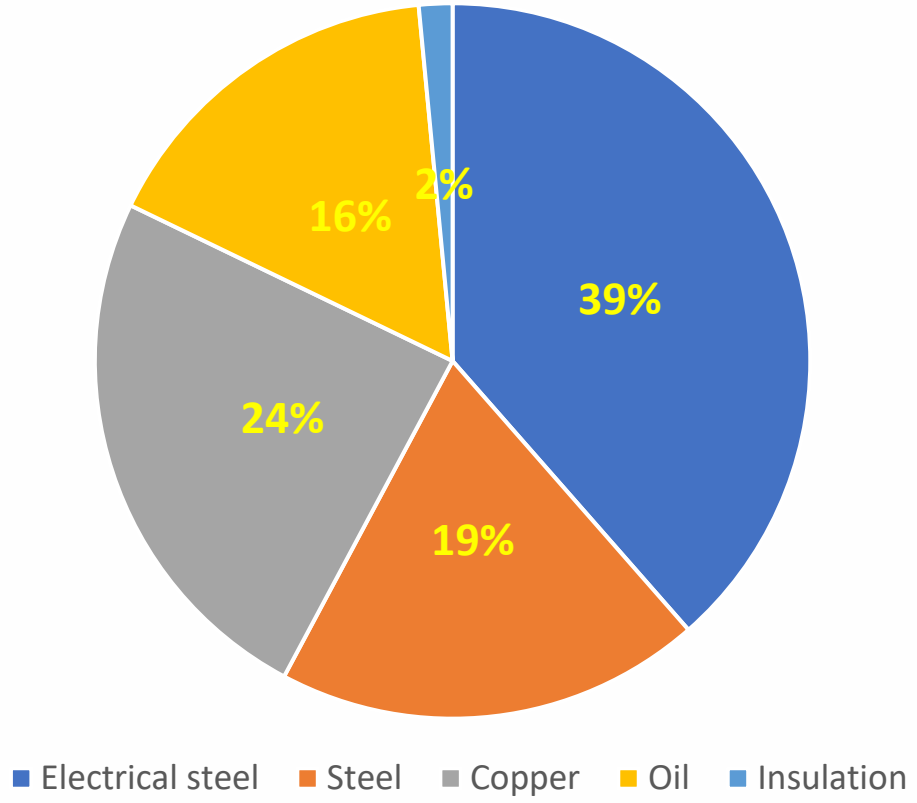
Carbon Footprint of an LPT

765 KV, 500 MVA 1 Ph Auto Transformer				
	Quantity(MT)	CO2/MT	CO2 (MT)	Share
Electrical steel	99	3.00	297	38%
Steel	93	2.50	233	30%
Copper	30	4.74	142	18%
Oil	70	1.21	85	11%
Insulation	16	1.18	19	2%
Transformer weight	339	2.29	775	



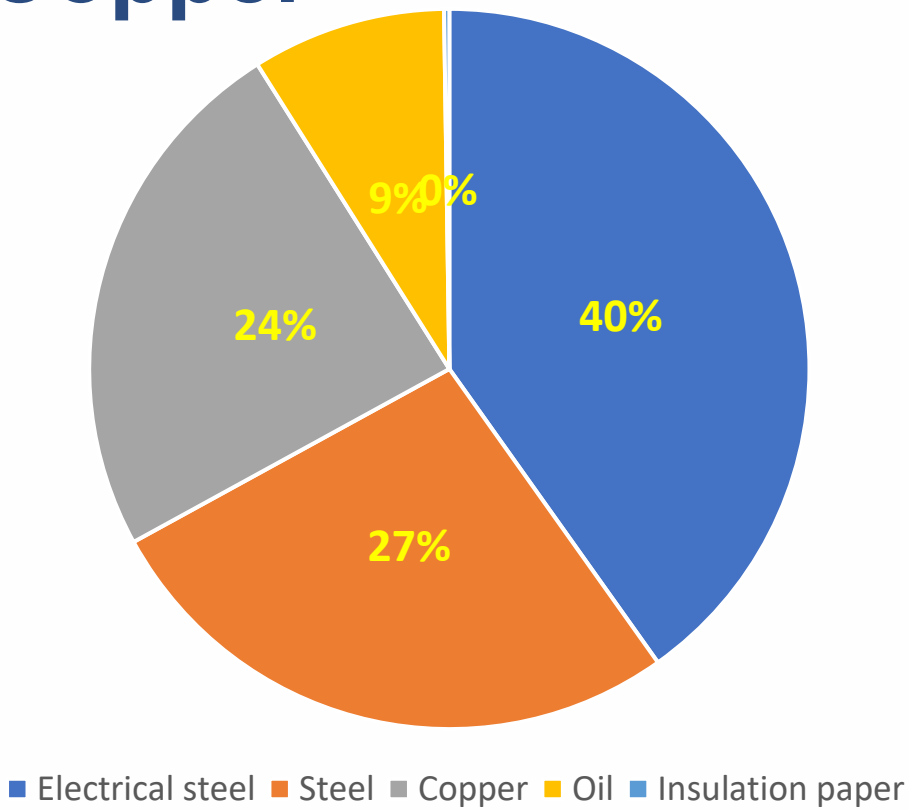
Carbon Footprint of an SPT

110 kv, 25 MVA				
	Quantity(MT)	CO2/MT	CO2 (MT)	Share
Electrical steel	20	3.00	60	39%
Steel	12	2.50	30	19%
Copper	8	4.74	38	24%
Oil	21	1.21	25	16%
Insulation	2	1.18	2	2%
Transformer weight	70	2.22	156	



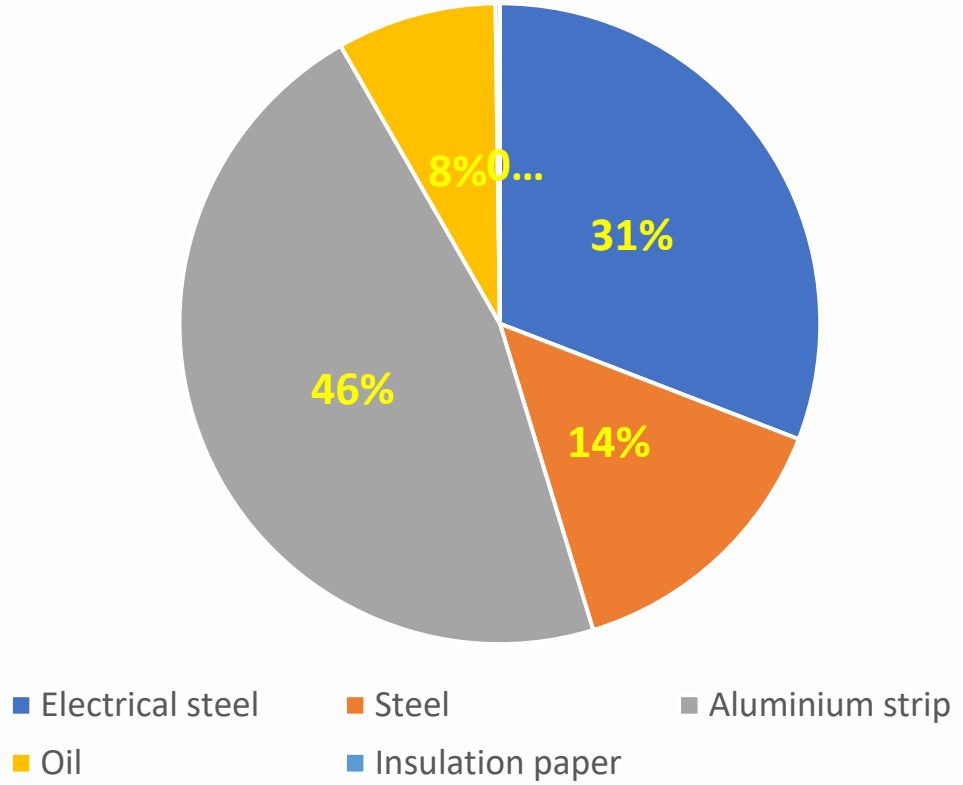
Carbon Footprint of a DT with Copper

12 kv, 250 kVA distribution transformer				
	Quantity(MT)	CO2/MT	CO2 (MT)	Share
Electrical steel	0.42	3.00	1.3	40%
Steel	0.337	2.50	0.8	27%
Copper	0.159	4.74	0.8	24%
Oil	0.226	1.21	0.3	9%
Insulation paper	0.009	0.82	0.0	0%
Transformer weight	1.266	2.48	3.1	



Carbon Footprint of a DT with Aluminum

36 kv, 1000 kVA distribution transformer				
	Quantity(MT)	CO2/MT	CO2 (MT)	Share
Electrical steel	1.161	3.00	3.5	31%
Steel	0.651	2.50	1.6	14%
Aluminium strip	0.291	18	5.2	46%
Oil	0.752	1.21	0.9	8%
Insulation paper	0.03	0.82	0.0	0%
Transformer weight	3.174	3.55	11.3	



Transportation

Mode of transport	CO_2 share
Passenger travel	7.1%
Road freight	4.8%
Aviation	1.9%
Shipping	1.7%
Rail	0.4%
Pipeline	0.3%
Total transport	**16.2%**

- Transportation sector is responsible for 16.2% of the global CO_2 emissions. It is one of the largest contributors.
- Out of this, industrial transport (road freight + shipping) is 6.5%
- Transportation Carbon footprint comparison:

  Air: 8X

  Road: 1X

  Rail: 4X

  Sea: 8X
- Large power transformers are especially heavy and bulky, and occasionally transported over long distances, sometimes intercontinental. This is a very carbon-intensive process.
- The transport of power transformers may generate emissions of 10–25% of the total emissions of raw materials, depending on weight, dimensions, and distance
- This ratio may be 5–10% for distribution transformers

Transformer Production

- Hydrogen-based reduction and smelting trials
- Transformer production is not energy intensive, and the carbon footprint is a tiny fraction of the emission of raw materials (only 2 %)
- Energy saving efforts in a transformer factory will not generate a significant impact on the emissions of the whole transformer life-cycle, although the cost reduction of this effort can be significant
- A larger impact can be achieved if the factory can switch to renewable energy (Scope 2 becomes zero)
- Much larger emission reductions could be achieved through 2 actions:

1. Waste reduction: This will have a very high impact on carbon emissions. If all scrap rates can be reduced by 1 percentage points, this will generate a reduction in the carbon footprint, which is equal to the half of the total production emissions. Conductors have an especially high potential for scrap reduction. Due to MOQ and quantity tolerance stacking (design + ordering + supplier), transformer factories typically generate high scrap for the conductors.
2. Recycling: Recycling uses significantly less energy; for example, 80%–90% less for copper, than mining and smelting primary metal. The recycling process of aluminium requires a lot less energy than primary aluminium production, and thus emits less CO_2 – approximately 0.5 tons per ton of aluminium (95% less). Steel, copper, aluminium, paper, and pressboard scraps should be accumulated and returned to the original suppliers whenever possible. Special deals could be discussed with the suppliers to receive recycled products whenever feasible.

Transformer Operation

- Hydrogen-based reduction and smelting trials
- In the whole lifecycle of transformers, by far the largest share of CO_2 emissions is generated during the operation stage
- The average life of a transformer is assumed to be around 40 years, which is pushing up the share of emissions of this stage
- The main driver of emissions during transformer operation is no load losses and load losses
- No load losses depend on the choice of electrical steel grade. The lowest GOES grade in the market is M5, with core loss values of 1.30 W/kg, and the best available grade has a core loss value of 0.65 W/kg, although very limited in quantity. The choice of the grade will depend on customer specifications. If there is no demand regarding the core loss performance of the transformer , the designer will select M5. And for very high loss capitalization, the choice would be the best available grade.
- Load losses are strongly influenced by the choice of conductor. Aluminium is cheaper, but will generate higher losses. We have also seen that Aluminium has a higher CO_2 footprint as a raw material as well. Copper will perform better, but the cost is higher. This choice is also typically made by the customer.
- Transformer producers should try to convince the customer to adopt the TCO concept and specify higher performance for the transformer. This will have a significant impact on the emissions during the operation stage. With the right choices, emissions during operation can be reduced by 30-40%.