Design Report

LOT 2: Distribution and Power Transformers

1250 kVA & 2000 kVA Three-Phase Cast-Coil Dry-Type Transformers

An assessment of the relationship between energy-efficiency and price

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DISCLAIMER

ACKNOWLEDGEMENTS

The transformer designs presented in this report were prepared through a joint working relationship established by CLASP's Europe office and two cast-coil dry-type transformer design engineers based in Poland, Janusz Ostrowski and Ivo Pinkiewicz. Janusz and Ivo used their design software and experience to prepare a set of designs for three-phase 50 Hz cast-coil dry-type transformers, spanning a range of efficiency values. Michael Scholand of Navigant Consulting Europe assisted CLASP in this undertaking, including liaising with the design team, and preparing this report. CLASP would also like to thank Paul Goethe and Nahid Pempin of Optimized Program Service in Cleveland, Ohio (USA) for their review of the completed designs presented in this report.

COMMENTS

Stakeholders are invited to provide comment to CLASP on the designs presented and the cost-breakdowns shown in this report. This report relies primarily on the material cost inputs published in the January 2011 Final Report VITO Preparatory Study, Chapter 2, Table 2-20 "Overview of material prices for liquid immersed and dry-type transformers in €/kg". A PDF of the VITO study is available at: http://www.ecotransformer.org/docs/EuP_TransformersTask_1_7.pdf). These material prices are based on those published by the US Department of Energy (September 2007) in their Distribution Transformer regulatory proceeding with supplemental input from European stakeholders in August and September of 2009. There are, however, some other cost assumptions and estimates added by CLASP, including a labour and manufacturer mark-ups which have been added to build up to a final manufacturer's selling price. Please submit any comments on this report to:

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ABOUT CLASP

Established in 1999, CLASP is an independent non-profit organisation serving as a resource and voice for energy efficiency worldwide. CLASP has provided technical assistance on standards and labelling (S&L) in over 50 countries, supporting and promoting energy-efficiency in appliances, lighting and equipment. In 2009, CLASP became a ClimateWorks Foundation (CWF) global Best Practice Network on S&L. CWF funding has enabled CLASP to expand its activities globally to reduce the emission of greenhouse gases that cause climate change. Currently, CLASP has offices or programmes in China, the European Union, India, Latin-American and the United States.

CLASP's primary objective is to identify and respond to the analysis needs of S&L practitioners in targeted countries and regions while making the highest quality technical information on S&L best practice available globally. To this end, CLASP works on the ground providing technical analysis and expertise to national governments and local partners; aggregates resources; assembles project teams from diverse and highly-qualified organizations; oversees projects; partners and collaborates with policy makers and members of industry alike; and disseminates information for maximum impact. This report was prepared for and provided by CLASP's Europe office as part of its effort to strengthen the European Commission's regulatory analysis on power and distribution transformers. For more information about CLASP, please visit our website:
http://www.clasponline.org/index.php

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Acronyms and Abbreviations

BOM	Bill of Materials
°C	degrees Celsius
CLASP	Collaborative Labeling and Appliance Standards Program
DER	Distributed Energy Resources
DG	Distributed Gap (i.e., a type of wound core)
EC	European Commission
EN	European Standard (Européenne Norme)
EU	European Union
kV	kilovolt (i.e., thousand volts)
kVA	kilovolt-Ampere
M_	Grain-oriented silicon steel, M6, M4, M3, M2 (see section 2.2)
M-0H	Laser-scribed domain refined silicon steel
OPS	Optimized Program Service
R&D	Research and Development
SA1	Amorphous core material
US	United States
W	Watts

1 Executive Summary

In support of the European Commission's analysis of Distribution and Power Transformers, CLASP has undertaken two studies on the relationship between manufacturer's selling price and efficiency covering five of the seven base case transformers evaluated by the Commission. In August 2010, CLASP published a design report on three oil-immersed transformers:

- 400 kVA oil-immersed three-phase unit, representing distribution transformers
- 1000 kVA oil-immersed three-phase unit, representing industry transformers
- 2000 kVA oil-immersed three-phase unit, representing distributed energy resources (DER) transformers

In this report, CLASP is publishing design results on two cast-coil dry-type transformers:

- 1250 kVA cast-coil dry-type three-phase unit, representing industry transformers
- 2000 kVA cast-coil dry-type three-phase unit, representing distributed energy resources (DER) transformers

Understanding how the price of transformers increases as the efficiency improves is important because it enables an accurate assessment of life-cycle costs and associated payback periods. Generally, a transformer becomes more expensive as efficiency improves because it is incorporating either more material and/or better quality materials.

CLASP prepared designs in accordance with the manufacturer's questionnaire prepared by VITO and published in the Final Report Preparatory Study in January 2011 (see Annex B and C of the Preparatory Study). The table below presents the designs that were created, a baseline unit ("Eff0"), followed by designs with lower losses on core and coil, as specified in VITO's questionnaire. There were eight 1250 kVA and seven 2000 kVA designs created in this analysis – in total, 15 transformer designs. In each case, both stacked core and wound core designs were prepared. The stacked cores use grain-oriented electrical steel and the wound core designs use amorphous material.

Table 1-1. Table of Cast-Coil Dry-Type Transformer Designs Prepared

1250 kVA		2000 kVA	
Stacked Core	Wound Core	Stacked Core	Wound Core
Eff0 Eff1 Eff2 Eff3	Eff4 Eff5 Eff6 Eff7	Eff0 Eff1 Eff2	Eff3 Eff4 Eff5

The figure below illustrates the stacked and wound core-coil configurations used in these three-phase transformer designs. The cast-coil windings are represented by the yellow-shaded portions of the diagram and the core steel / amorphous material is shown in grey. Stacked cores were designed as three-legged mitred cores (on the left) and wound cores were designed using amorphous material in a five-legged wound core (on the right). It should be noted that this is a simplistic illustration, and the actual three-legged mitred cores designed for this study are cruciform, meaning they have a circular cross-section as opposed to square.

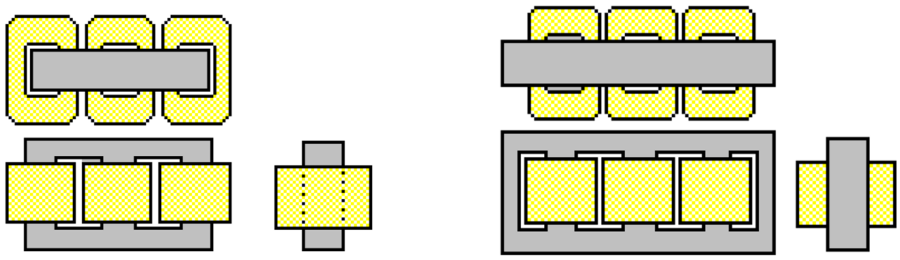


Figure 1-1. Core Construction Used for (a) Stacked and (b) Wound Cores

Designs were prepared taking into account the maximum losses and target impedance contained in harmonized document (HD 538) which will be superseded by EN 50541-1. A summary of the design results are presented in the following subsections for each of the two representative transformers. Subsequent chapters of this report describe the methodology followed, the inputs used and more detail on the results. There are eight transformer designs included in the Annexes to this report, two stacked and two wound core designs from each representative transformer.

1.1 Results for 1250 kVA Cast-Coil Three-Phase Dry-Type

The 1250 kVA three-phase cast-coil dry-type transformers were designed to operate on a 50 Hz system with a primary voltage of 11 kV and a secondary voltage of 600 V. The transformer has an average winding-temperature rise at rated current of 100°C, and a tap configuration of four 2½ percent taps—two above and two below the nominal output voltage.

The figure below presents the results of CLASP's analysis along with the designs that were published in the Final Report Preparatory Study (labelled as "VITO" in the graphic). CLASP prepared eight designs, four with conventional electrical steel and four with amorphous material. VITO prepared five designs, four with conventional electrical steel and one with amorphous material. In order to differentiate between the two different core types, the CLASP ones have diamonds for electrical steel and circles for amorphous material. The VITO designs have squares for electrical steel and triangles for amorphous material. Exponential curve-fits are assigned to both sets of designs, which depict the general relationship between the transformer manufacturer's selling price and efficiency.

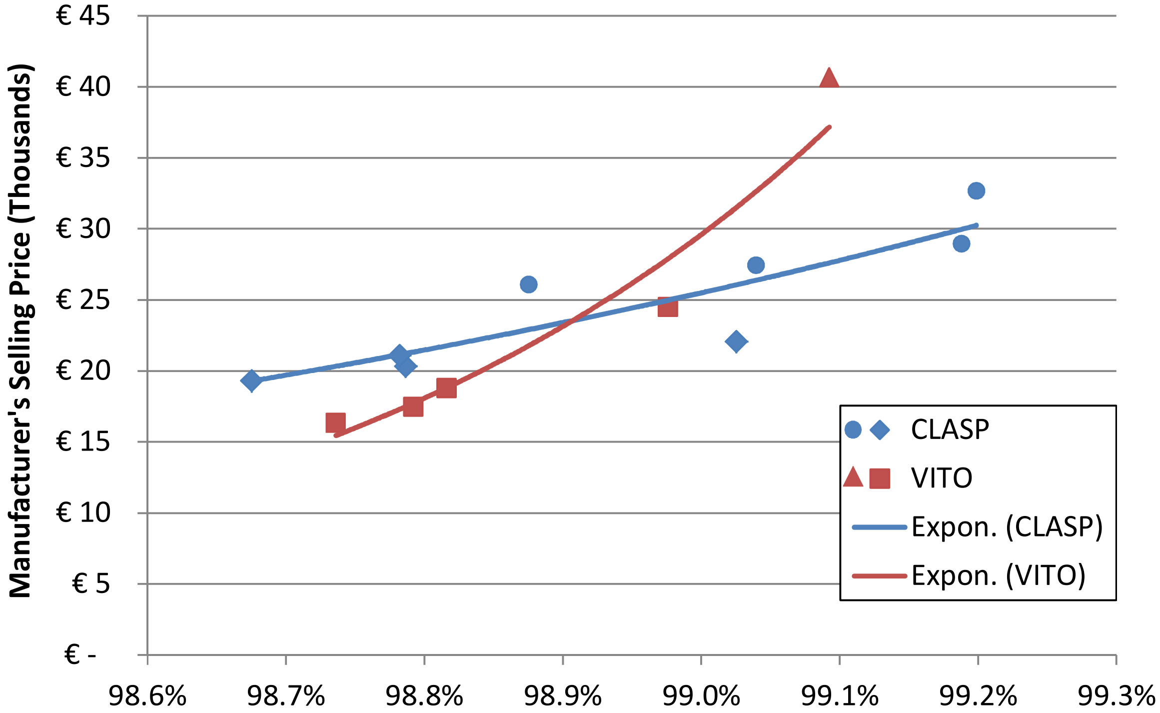


Figure 1-2. Price vs. Efficiency of VITO and CLASP 1250 kVA 3-Phase Cast-Coil Dry-Type

The designs published by VITO using conventional electrical steel appear to be in line with the manufacturing cost estimates prepared from the 1250 kVA transformer designs commissioned by CLASP. However, there appears to be a significant departure for the wound core amorphous designs, where VITO's design is more than €10k more expensive than a comparable CLASP design.

The table below presents tabular results and the corresponding relative costs for the CLASP designs prepared in this study, 1250 kVA three-phase cast-coil dry-type transformers.

Table 1-2. Indexed Price Increases Relative to Baseline for CLASP's Designs, 1250 kVA

BC3 – Industry Dry-Type Transformer 1250 kVA		C_0	B_0	A_0	Amorphous	
		2800 W	2100 W	1800 W	650 W	500 W
B_K	13,000 W	100%	105%	109%	135%	
A_K	11,000 W			114%	142%	
Amorphous	9000 W				150%	169%

The table below compares the transformer designs prepared on a cost basis and looks at the difference. For the conventional electrical steels, the two sets of designs are reasonably well aligned, although the VITO designs tend to be less expensive. The difference between the cost and efficiency relationship between the two design-sets increases with the performance of the transformer. While this can be seen in the conventional set of

transformer designs, it is even more evident for the amorphous core units, where the CLASP design is 32% lower than the VITO design.

Table 1-3. Price Comparison of 1250 kVA Three-Phase Cast-Coil Dry-Type Designs

Design Losses		CLASP Designs		VITO Designs		Difference of CLASP to VITO
Core (P_0)	Coil (P_K)	Efficiency	Price	Efficiency	Price	
2800 W	13,000 W	98.68%	€ 19,291	98.74%	€ 16,333	18.1%
2100 W	13,000 W	98.79%	€ 20,335	98.79%	€ 17,476	16.4%
1800 W	13,000 W	98.78%	€ 21,076	98.82%	€ 18,783	12.2%
1800 W	13,000 W	99.03%	€ 22,073	98.98%	€ 24,500	-9.9%
650 W*	11,000 W	98.88%	€ 26,085			
650 W*	11,000 W	99.04%	€ 27,446	99.09%	€ 40,669	-32.5%
650 W*	9000 W	99.19%	€ 28,961			
500 W*	9000 W	99.20%	€ 32,672			

* Amorphous core transformer designs.

Improving efficiency from the base case model of C0Bk (2800 W, 13,000 W) up to A0Ak (1800 W, 11,000 W) has an average incremental cost per one-hundredth percent improvement in efficiency of €79 for the CLASP designs and €340 for the VITO designs. Part of the reason for this difference in incremental cost for efficiency improvement is the fact that the CLASP baseline transformer is more expensive by approximately €3000. However, the VITO design surpasses the CLASP cost-curve, with the VITO A0Ak model costing €2,500 more.

It is also interesting to note that for the one amorphous VITO design, there is a marked jump in price – going from €24,500 to €40,669 as the efficiency increases by 0.11%, from 98.98% to 99.09%. For the CLASP amorphous designs, there is a step increase (approximately €5k at 99.03-99.04% efficient), however the relationship between cost and efficiency is more continuous, as depicted in Figure 1-2 above.

1.2 Results for 2000 kVA Cast-Coil Three-Phase Dry-Type

The 2000 kVA three-phase cast-coil dry-type transformers were designed to operate on a 50 Hz system with a primary voltage of 11 kV and a secondary voltage of 600 V. The transformer has an average winding-temperature rise at rated current of 100°C, and a tap configuration of four 2½ percent taps—two above and two below the nominal output voltage.

The figure below presents the results of CLASP's analysis along with the designs that were published in the Final Report Preparatory Study (labelled as "VITO" in the graphic). CLASP prepared six designs, three with conventional electrical steel and three with amorphous

material. VITO prepared three designs with conventional electrical steel, and did not have a transformer design using amorphous material. In order to differentiate between the two different core types, the CLASP designs have diamonds for electrical steel and circles for amorphous material. The VITO designs have squares for electrical steel. Exponential curve-fits are assigned to both sets of designs, which depict the general relationship between the transformer manufacturer's selling price and efficiency.

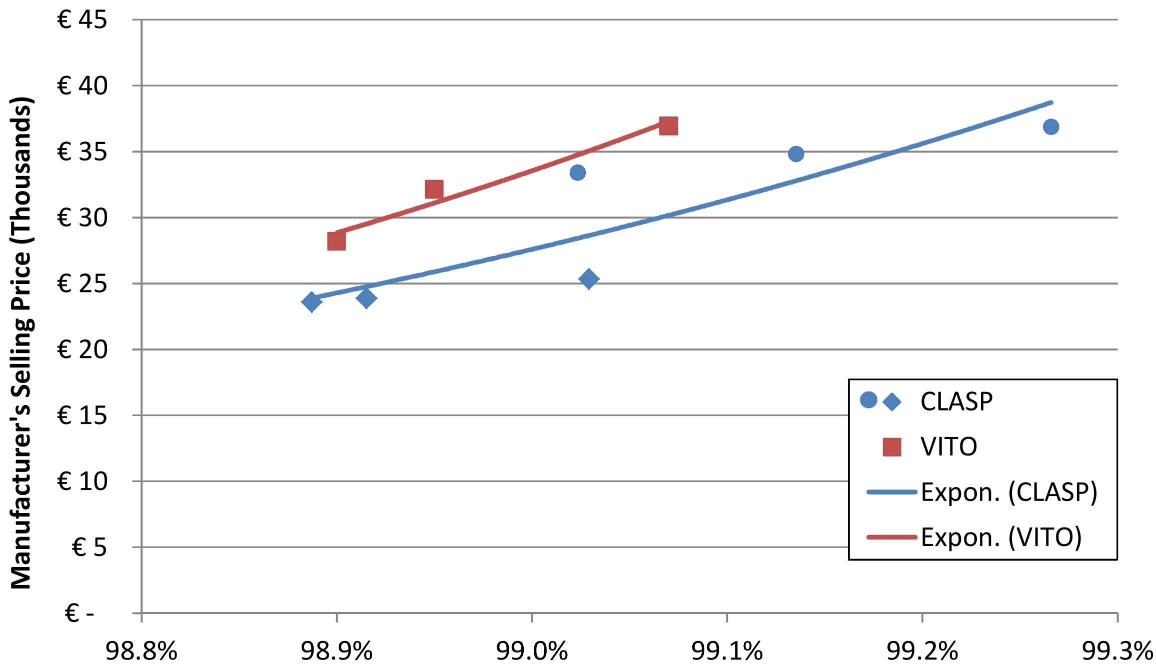


Figure 1-3. Price vs. Efficiency of VITO and CLASP 2000 kVA 3-Phase Cast-Coil Dry-Type

The designs published by VITO using conventional electrical steel appear to be more expensive than the designs prepared by CLASP. Furthermore, the slope of the cost-efficiency lines is different for the two sets of designs. The VITO slope is steeper, implying that increasing efficiency is more expensive than the slope of the CLASP line. Note that comparing just the silicon steel designs, the VITO designs are approximately €5-7k more expensive with a steeper efficiency slope. CLASP's incorporation of amorphous designs into this design dataset also shows the potential to achieve higher efficiency points. The most efficient design is 99.27%, and is the same price as the most efficient VITO conventional electrical steel design at 99.07%.

The table below presents tabular results and the corresponding relative costs for the designs under consideration for the 2000 kVA three-phase cast-coil dry-type transformer.

Table 1-4. Indexed Price Increases Relative to Baseline for CLASP's Designs, 2000 kVA

BC 6 DER dry-type transformer 2.0 MVA		C0	B0	A0	Amorphous
		4000 W	3000 W	2600 W	950 W
Bk	18000 W	100%	101%		142%
Ak	16000 W			107%	148%
Amorphous	13000 W				156%

The table below compares the transformer designs prepared on a cost basis and looks at the difference. For the conventional electrical steels (only comparison possible), CLASP is consistently less expensive than VITO. On average, CLASP is approximately 25% less expensive, which is very significant considering both designs were based on the same set of material costs and the efficiency levels are about comparable. One immediate difference that is evident is the fact that VITO's designs are built using aluminium windings and CLASP's designs are using copper. The current density per unit cross-sectional area of aluminium is lower than copper, which results in larger windings and larger cores, driving up the cost.

Table 1-5. Price Comparison of 2000 kVA Three-Phase Cast-Coil Dry-Type Designs

Design Losses		CLASP Designs		VITO Designs		Difference of CLASP to VITO
Core (P0)	Coil (Pk)	Efficiency	Price	Efficiency	Price	
4000 W	18000 W	98.89%	€ 23,584	98.90%	€ 28,192	-16.3%
3000 W	18000 W	98.92%	€ 23,874	98.95%	€ 32,139	-25.7%
2600 W	16000 W	99.03%	€ 25,330	99.07%	€ 36,931	-31.4%
950 W*	18000 W	99.02%	€ 33,406			
950 W*	16000 W	99.14%	€ 34,818			
950 W*	13000 W	99.27%	€ 36,892			

* Amorphous core transformer designs.

Improving efficiency in the conventional steel designs from the base case model of C0Bk (4000 W, 18,000 W) up to A0Ak (2600 W, 16,000 W) has an average incremental cost per one-hundredth percent improvement in efficiency of €123 for the CLASP designs and €514 for the VITO designs. This difference reflects the comment made above relating to the slope of efficiency in the two design datasets – the VITO designs have a much steeper slope to their efficiency curve in the conventional steel designs. Overall, the VITO designs are more expensive than the CLASP designs and increase in cost relative to efficiency more quickly.

Part of the reason the VITO designs in the Preparatory Study are more expensive is because they are larger designs, containing more material. These larger designs incorporate more core steel and windings, which drives up the manufacturer's selling price. CLASP prepared the following table as a comparison between a few 2000 kVA cast-coil transformer designs

that are commercially available in Europe. From this comparison, it would appear that the VITO designs may be too heavy for this representative rating. The CLASP designs were prepared with copper windings while the other three shown in the table all use aluminium. CLASP's design team estimates that designing with aluminium increases the weight of a cast-coil transformer near this kVA rating by approximately 8%, thus the CLASP design scaled to use aluminium windings would weigh approximately 4245 kg. Compared this total weight with that of the published weights of ABB, GEAFOL Siemens and VITO (all of which incorporate aluminium windings), the VITO design is approximately 13 to 23% heavier. This difference will, in part, account for the VITO transformer costs being higher than CLASP's, as depicted in Figure 1-3.

Table 1-6. Comparison of 2000 kVA Cast Coil Weights

Company	Weight	NL	LL	Efficiency	Core steel	Windings
	(kg)	*(W)*	*(W)*	*(%)*	*(kg)*	*(kg)*
CLASP (Copper)	4023	3835	18,419	98.89%	2414	1015
VITO	5225	4000	18,000	98.90%	3569	841
ABB	4630	3600	18,000	98.92%	n/a	n/a
GEAFOL Siemens	4440	3600	16,000	99.02%	n/a	n/a

1.3 Policy Implications of the Findings

CLASP's design work on these two representative kVA ratings analysed in the Preparatory Study has identified problems with both models. In developing the Working Group and preparing the Consultation Forum document, the Commission may wish to conduct further analysis on these two cast-coil dry-type units.

For the 1250 kVA unit, considering only the conventional silicon electrical steels, the two sets of designs are reasonably well aligned, although the VITO designs tend to be less expensive than those prepared by CLASP. There is a significant departure however between the amorphous-core designs, where the CLASP design is 32% lower than the VITO design. Due to the very high price associated with the VITO design, the price-slope of efficiency improvement is 4 times steeper for VITO than it is for CLASP (€79 for the CLASP designs and €340 for the VITO designs). The VITO amorphous design jumps in price going from €24,500 to €40,669 at a maximum efficiency of 99.09%. The CLASP amorphous designs span that efficiency level, and go even higher, achieving 99.20% at a lower price - €32,672.

For the 2000 kVA unit, VITO did not have any amorphous designs, which prevents the full range of efficiency levels from being considered. Furthermore, for those conventional silicon steel designs that were prepared by VITO, the manufacturers selling prices are considerably more expensive and VITO's price-slope of efficiency improvement is steeper than CLASPs. Having a steeper slope implies that increasing efficiency is more expensive than it actually is, with optimised transformer designs. And, looking just at the silicon steel

designs, VITO's transformers are €5-7k more expensive, representing a 25% price premium. CLASP also compared its own and VITO's designs against available manufacturer catalogue data, and found that the VITO transformers are too heavy and thus are not representative of the market.

Overall, due to the fact that the cast-coil dry-type transformers presented in the Final Report Preparatory Study do not consider technically feasible design options (i.e., amorphous core), are over-built (i.e., too heavy, making them too expensive) and the designs are not optimised (i.e., in all cases, the slope of the price-efficiency curve is too steep), CLASP has significant concerns about the findings presented in the Final Report Preparatory Study for these transformers. CLASP requests that this new design information be taken into consideration by the Consultation Forum when preparing the draft regulation.

2 Designs for 1250 kVA Cast-Coil Dry-Type Transformer (BC3)

Basecase Transformer #3 (BC3) represents cast-coil dry-type industrial transformers. The rating selected for this basecase unit is the 1250 kVA three-phase transformer. The following are the technical specifications used as inputs by the design team:

Type: Three-phase, cast-coil, dry-type
kVA: 1250
Primary: 11 kilovolts at 50 Hz
Secondary: 600 volts
Temp Class: 155°C (above ambient, assumed 20°C)
Winding Configuration: Dy5
Cores: a) Silicon steel in mitred stacked core, cruciform, 3-leg
b) Amorphous material in wound core, distributed gap, 5-leg
Taps: +/- 2 x 2.5% above and below the nominal
Impedance: 6%

VITO developed and published a matrix of core and winding losses as a survey tool to facilitate input from manufacturers on the relationship between price and efficiency. The table presented below contains the loss and price information for the 1250 kVA transformer. VITO requested input from manufacturers on the percentage price increase for each of the incremental improvements from the Eff0 transformer. To facilitate a comparison with the Final Report Preparatory Study, CLASP adopted this approach when engaging its design team to prepare the designs presented in this report.

Table 2-1. VITO Survey Tool to Quantify Price Increases Relative to Efficiency, 1250 kVA

BC 3 Industry dry-type transformer 1.25 MVA		C_0	B_0	A_0	Amorphous	
		2800 W	2100 W	1800 W	650 W	500 W
		78 dB	67dB	67dB	70dB	70dB
B_K	13,000 W	Eff0	Eff1	Eff2	Eff4	
A_K	11,000 W			Eff3	Eff5	
Amorphous	9000 W				Eff6	Eff7

Thus, there are eight transformers that were prepared by CLASP's transformer design team:

a) Stacked cruciform core type step-lap, silicon steel

- Baseline design Eff0: P_0 = 2800 W, P_K = 13,000 W
- Eff1: P_0 = 2100 W, P_K = 13,000 W
- Eff2: P_0 = 1800 W, P_K = 13,000 W
- Eff3: P_0 = 1800 W, P_K = 11,000 W

b) Wound 5 legs core, Amorphous, 2605 SA1

- Eff4: P_0 = 650 W, P_K = 13,000 W
- Eff5: P_0 = 650 W, P_K = 11,000 W
- Eff6: P_0 = 650 W, P_K = 9000 W
- Eff7: P_0 = 500 W, P_K = 9000 W

The cost of a 1250 kVA increases with improvements in the efficiency, as shown in the table below.

Table 2-2. CLASP Designs Prepared for 1250 kVA Cast-Coil Dry-Type Transformer

	EFF0	EFF1	EFF2	EFF3	EFF4	EFF5	EFF6	EFF7
Power rating:	1250	1250	1250	1250	1250	1250	1250	1250
Phases:	3	3	3	3	3	3	3	3
Number of legs:	3-leg	3-leg	3-leg	3-leg	5-leg	5-leg	5-leg	5-leg
Frequency:	50 Hz	50 Hz	50 Hz	50 Hz	50 Hz	50 Hz	50 Hz	50 Hz
Primary (kilovolts)	11	11	11	11	11	11	11	11
Secondary (volts)	600	600	600	600	600	600	600	600
Ref. temperature (°C):	120	120	120	120	120	120	120	120
Ambient (°C):	20	20	20	20	20	20	20	20
Winding Configuration:	Dyn5	Dyn5	Dyn5	Dyn5	Dyn5	Dyn5	Dyn5	Dyn5
Core:	Stacked	Stacked	Stacked	Stacked	Wound	Wound	Wound	Wound
Core Type:	Mitred	Mitred	Mitred	Mitred	DG	DG	DG	DG
Core Mat'l:	M6	M3	M3	M-0H	SA1	SA1	SA1	SA1
HV Conductor Mat'l:	Cu	Cu	Cu	Cu	Cu	Cu	Cu	Cu
LV Conductor Mat'l:	Cu	Cu	Cu	Cu	Cu	Cu	Cu	Cu
Core Losses:	2887	2204	1906	1721	636	638	640	528
Coil Losses:	13,671	12,965	13,317	10,462	13,423	11,367	9512	9488
Total weight (kg):	3036	3035	3343	3373	3593	3775	3992	4753
Efficiency (100% load):	98.68%	98.79%	98.78%	99.03%	98.88%	99.04%	99.19%	99.20%
Selling Price:	€19,291	€20,335	€21,076	€22,073	€26,085	€27,446	€28,961	€32,672
% Increase over Eff0:		5%	9%	14%	35%	42%	50%	69%

Four designs were selected from this database of designs for presentation in this chapter of the report, providing detail on the bill of materials (BOM) and the performance of the designs. The four designs selected were:

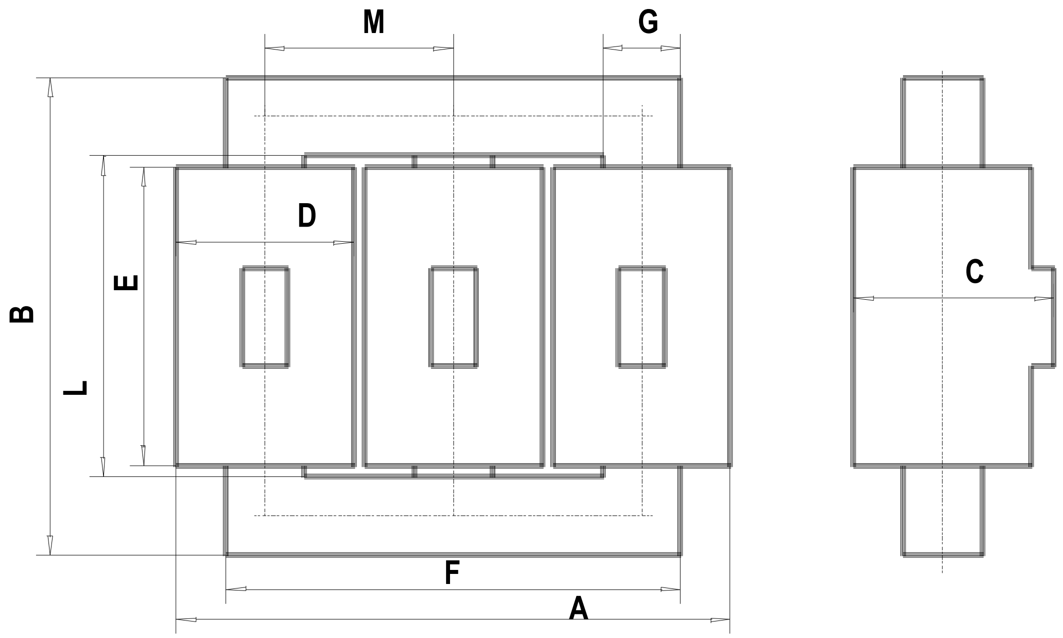
- EFF0 – a 1250 kVA cast-coil transformer built with M6 core steel in a cruciform circular stack, with losses of 2887 W in the core and 13,671 W in the coil at full load.
- EFF2 – a 1250 kVA cast-coil transformer built with M3 core steel in a cruciform circular stack, with losses of 1721 W in the core and 10,462 W in the coil at full load.
- EFF5 – a 1250 kVA cast-coil transformer built with amorphous material in a 5-leg wound core configuration, with losses of 638 W in the core and 11,367 W in the coil at full load.
- EFF7 – a 1250 kVA cast-coil transformer built with amorphous material in a 5-leg wound core configuration, with losses of 528 W in the core and 9488 W in the coil at full load.

2.1 EFF0 BOM for 1250 kVA Cast-Coil Dry-Type M6 in a Cruciform Stack

Main Data

Rated Power	1250 kVA
Rated Voltage	11,000 V ±2x2.5%/600 V
Impedance	6.0%
Winding configuration	Dyn5
Core material	M6
Type of core	Stacked

Main dimensions of transformer [mm]



Where:

A = 1643	F = 1380
B = 1510	G = 265
C = 603	L = 990
D = 523	M = 560
E = 920	

Data of core

Diameter of column	265 mm
Cross section of column and yoke	484.33 cm^2
Induction in column	1.611 T
Weight of core	2138.9 kg
No-load losses	**2887 W**

Primary winding

Turns

Tap	+5.0%	+2.5%	0%	- 2.5%	- 5.0%
Turns	667	651	635	619	603

Material	Cu
Dimension of wire	Ø 4.0/4.15 mm
Current density	3.16 A/mm^2
Inner Diameter	437 mm
Cooling canal	16 mm
Outer Diameter	523 mm
Winding resistance-120^{o}C	1.919 Ω
Weight of wire of windings	3x112.6 kg
Weight of resin	3x49.5 kg
Weight of strips for axial canal	3x5.3 kg
Load losses	3x2977.4 W

Secondary winding

Turns	20
Material	Cu
Dimension of wire	foil 2x(0.61x400) mm
Current density	2.46 A/mm^2
Inner Diameter	277 mm
Cooling canals	2 x12 mm
Outer Diameter	367 mm
Winding resistance-120^{o}C	0.001011 Ω
Weight of windings foil	3x87.9 kg
Weight of resin	3x19.6 kg
Weight of strips for axial canal	3x4.8 kg
Load losses	3x1579.7 W

Total load losses of transformer	**13,671 W**
Impedance	**5.74%**
Total weight of transformer	**3036 kg**

The following table provides the BOM prepared by the transformer design team. This BOM uses the raw material prices given in section 2.2 of this report, which are derived from the Final Report Preparatory Study (January 2011). These materials are then marked up at the bottom of the table to allow for factory overheads and non-production mark-ups (see section 2.2 of this report). The sum of the raw material costs, labour costs and mark-ups totals to the manufacturer's selling price. This table provides the BOM for 1250 kVA transformer with M6 core steel, built in a cruciform stack. This transformer has an 11 kV primary with copper wire and 600 V secondary with copper strip.

Table 2-3. Bill of Materials and Labour for 1250 kVA M6 in a Cruciform Stack (EFF0)

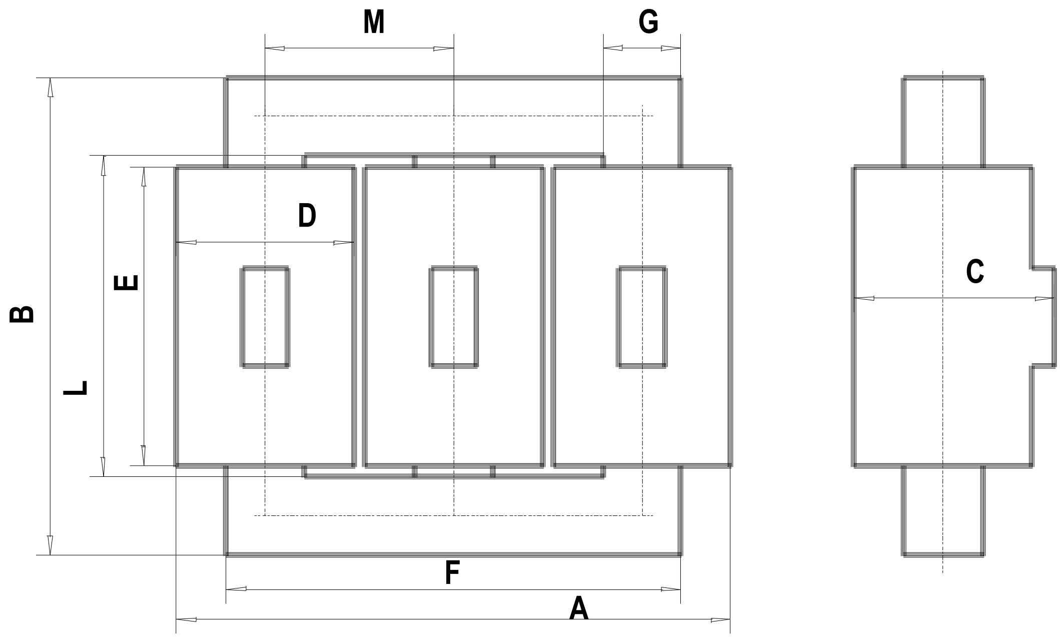
Material item	Type	Quantity	Each	Total
Core material*	M6 Grain-Oriented Silicon Steel	2,139	€ 1.60	€ 3,422
Primary Winding*	Copper wire Ø 4.0/4.15 mm	338	€ 4.85	€ 1,638
Secondary Winding*	Copper foil 2x(0,61x400) (kg)	264	€ 5.05	€ 1,332
Strips for axial canal	resiglass	30	€ 2.54	€ 77
Dielectric*	Resin kg	207	€ 16.82	€ 3,488
Transformer Cabinet	Kilograms	303	€ 0.74	€ 224
High Voltage Terminals	12kV, 100A	3	€ 30.00	€ 90
Low Voltage terminals	1 kV, 1500 A	4	€ 25.00	€ 100
Hardware and Clamps	misc. & nameplate		€ 150.00	€ 150
Scrap factor (applies to items with * above)			1.00%	€ 99
		Total Material Cost		€ 10,621
Labour item	**Description**	**Hours**	**€/hr**	**Total**
Lead Dressing	Prepare leads after winding	0.75	€ 60.00	€ 45
Handling and Slitting	Working with core steel	0.77	€ 60.00	€ 46
Winding the Primary	Varies with N turns	20.01	€ 60.00	€ 1,201
Winding the Secondary	Varies with N turns	4.50	€ 60.00	€ 270
Inspection	Quality assurance check	0.25	€ 60.00	€ 15
Resin Baking windings	Vacuum resin-impregn. process	6.00	€ 60.00	€ 360
Core Assembly	Assemble around coils, varies	8.35	€ 60.00	€ 501
Enclosure Forming and Painting	Manufacture enclosures	6.00	€ 60.00	€ 360
Final Assembly	Clamping winding on core	6.00	€ 60.00	€ 360
Preliminary Test on Windings	Check turns ratio, resistance	0.50	€ 60.00	€ 30
Final Test Assembled unit test	Assembled unit test	0.75	€ 60.00	€ 45
Packing and Pallet Loading	Clamping, wrapping and other	2.00	€ 60.00	€ 120
Marking and Miscellaneous	Labelling bushings, etc.	2.20	€ 60.00	€ 132
		Total Labour Cost		€ 3,485
Manufacturing Cost (Total Material & Total Labour)				€ 14,105
Factory Overhead (Applied to Material Costs Only)		12.5%		€ 1,328
Non-production Cost Markup		25%		€ 3,858
Manufacturer Selling Price				€ 19,291

2.2 EFF2 BOM for 1250 kVA Cast-Coil Dry-Type M3 in a Cruciform Stack

Main Data

Rated Power	1250 kVA
Rated Voltage	11,000 V ±2x2.5%/600 V
Impedance	6.0%
Winding configuration	Dyn5
Core material	M3
Type of core	Stacked, 3 leg

Main dimensions of transformer [mm]



Where:

A = 1680	F = 1400
B = 1420	G = 276
C = 620	L = 900
D = 540	M = 570
E = 830	

Data of core

Diameter of column	276 mm
Cross section of column and yoke	521.7 cm^2
Induction in column	1.495 T
Weight of core	2207.2 kg
No-load losses	**1906 W**

Primary winding

Turns

Tap	+5.0%	+2.5%	0%	- 2.5%	- 5.0%
Turns	667	651	635	619	603

Material	Cu
Dimension of wire	Ø 4.2/4.35
Current density	2.74 A/mm^2
Inner Diameter	449 mm
Cooling canal	16 mm
Outer Diameter	540 mm
Winding resistance-120^{o}C	1.786 Ω
Weight of wire of windings	3x127.8 kg
Weight of resin	3x56.8 kg
Weight of strips for axial canal	3x5.4 kg
Load losses	3x2771.1 W
Mean temperature rise	97.6^{o}C

Secondary winding

Turns	20
Material	Cu
Dimension of wire	foil 2x (0.63x380) mm
Current density	2.51 A/mm^2
Inner Diameter	288 mm
Cooling canals	2x12 mm
Outer Diameter	379 mm
Winding resistance-120^{o}C	0.001067 Ω
Weight of windings foil	3x89.3 kg
Weight of resin	3x20.7 kg
Weight of strips for axial canal	3x4.96 kg
Load losses	3x1667.8 W
Mean temperature rise	99.8^{o}C

Total load losses of transformer	**13,317 W**
Impedance	**6.06%**
Total weight of transformer	**3343 kg**

The following table provides the BOM prepared by the transformer design team. This BOM uses the raw material prices given in section 2.2 of this report, which are derived from the Final Report Preparatory Study (January 2011). These materials are then marked up at the bottom of the table to allow for factory overheads and non-production mark-ups (see section 2.2 of this report). The sum of the raw material costs, labour costs and mark-ups totals to the manufacturer's selling price. This table provides the BOM for 1250 kVA transformer with M3 core steel, built in a cruciform stack. This transformer has an 11 kV primary with copper wire and 600 V secondary with copper strip.

Table 2-4. Bill of Materials and Labour for 1250 kVA M3 in a Cruciform Stack (EFF2)

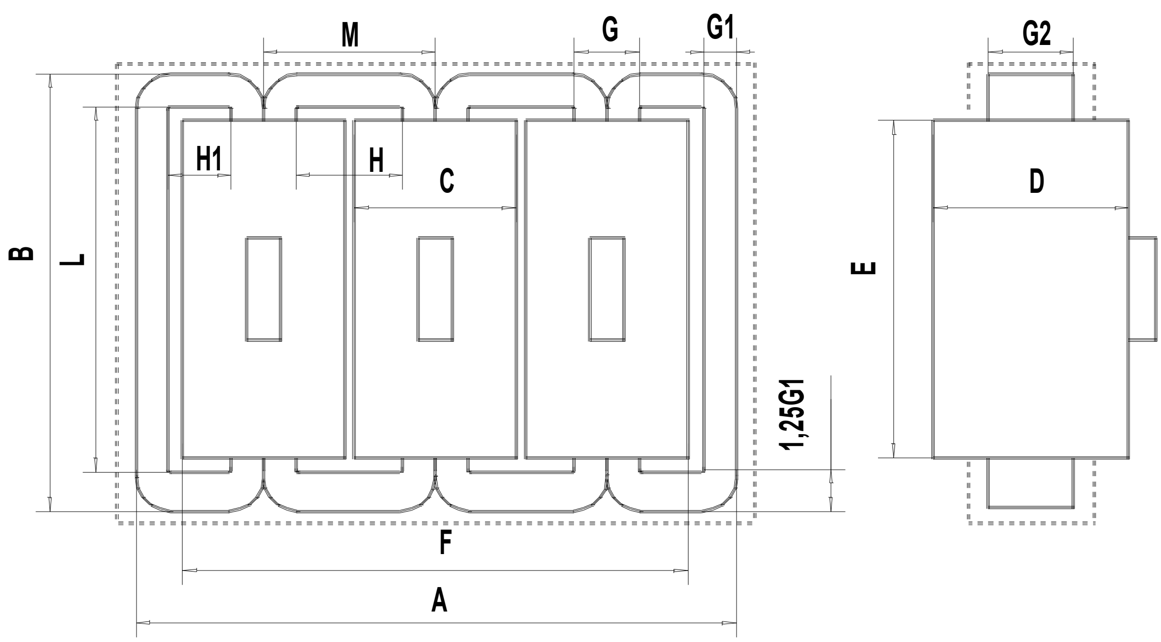
Material item	Type	Quantity	Each	Total
Core material*	M3 Grain-Oriented Silicon Steel	2,207	€ 1.81	€ 3,995
Primary Winding*	Copper wire Ø 4.2/4.35 (kg)	383	€ 4.85	€ 1,859
Secondary Winding*	Copper foil 2x (0.63x380) mm (kg)	268	€ 5.05	€ 1,353
Strips for axial canal	resiglass	31	€ 2.54	€ 79
Dielectric*	Resin kg	233	€ 16.82	€ 3,911
Transformer Cabinet	Kilograms	300	€ 0.74	€ 222
High Voltage Terminals	12kV, 100A	3	€ 30.00	€ 90
Low Voltage terminals	1 kV, 1500 A	4	€ 25.00	€ 100
Hardware and Clamps	misc. & nameplate		€ 152.00	€ 152
Scrap factor (applies to items with * above)			1.00%	€ 111
			Total Material Cost	€ 11,871
Labour item	**Description**	**Hours**	**€/hr**	**Total**
Lead Dressing	Prepare leads after winding	0.75	€ 60.00	€ 45
Handling and Slitting	Working with core steel	0.77	€ 60.00	€ 46
Winding the Primary	Varies with N turns	20.01	€ 60.00	€ 1,201
Winding the Secondary	Varies with N turns	4.50	€ 60.00	€ 270
Inspection	Quality assurance check	0.25	€ 60.00	€ 15
Resin Baking windings	Vacuum resin-impregn. process	6.00	€ 60.00	€ 360
Core Assembly	Assemble around coils, varies	8.69	€ 60.00	€ 522
Enclosure Forming and Painting	Manufacture enclosures	6.00	€ 60.00	€ 360
Final Assembly	Clamping winding on core	6.00	€ 60.00	€ 360
Preliminary Test on Windings	Check turns ratio, resistance	0.50	€ 60.00	€ 30
Final Test Assembled unit test	Assembled unit test	0.75	€ 60.00	€ 45
Packing and Pallet Loading	Clamping, wrapping and other	2.00	€ 60.00	€ 120
Marking and Miscellaneous	Labelling bushings, etc.	2.20	€ 60.00	€ 132
			Total Labour Cost	€ 3,506
Manufacturing Cost (Total Material & Total Labour)				€ 15,377
Factory Overhead (Applied to Material Costs Only)		12.5%		€ 1,484
Non-production Cost Markup		25%		€ 4,215
Manufacturer Selling Price				€ 21,076

2.3 EFF5 BOM for 1250 kVA Cast-Coil Dry-Type SA1 in a Wound Core

Main Data

Rated Power	1250 kVA
Rated Voltage	11,000 V ±2x2.5%/600 V
Impedance	6.0%
Winding configuration	Dyn5
Core material	Amorphous ribbon 2605 SA1.
Type of core	Wound, 5 leg

Main dimensions of transformer [mm]



Where:

A = 1723	G1 =91
B = 1200	G2 =364
C = 467	H =320
D = 649	H1 =178
E = 910	L =995
F =1471	M =502
G = 182	

Data of core

Dimension of main column	182x364 mm
Cross section of main column	556.48 cm^2
Induction in column	1.476 T
Weight of core	2222.4 kg
No-load losses	**638 W**

Primary winding

Turns

Tap	+5.0%	+2.5%	0%	- 2.5%	- 5.0%
Turns	**633**	**618**	**603**	**588**	**573**

Material	Cu
Dimension of wire	3.2x6.0/3.35x6.15mm
Current density	1.974 A/mm^2
Inner Dimensions	368x550 mm
Cooling canal	16 mm
Outer dimensions	467x649 mm
Winding resistance-120^{o}C	1.402 Ω
Weight of wire of windings	3x198.1kg
Weight of resin	3x62.5 kg
Weight of strips for axial canal	3x6.03 kg
Load losses	3x2174.9 W
Mean temperature rise	96.3^{o}C

Secondary winding

Turns	19
Material	Cu
Dimension of wire	foil 2x (0.7x420) mm
Current density	2.05 A/mm^2
Inner dimensions	206x388 mm
Cooling canals	2x12 mm
Outer dimensions	298x480 mm
Winding resistance-120^{o}C	0.0010327 Ω
Weight of windings foil	3x130.4 kg
Weight of resin	3x25.6 kg
Weight of strips for axial canal	3x5.63 kg
Load losses	3x1614.1 W
Mean temperature rise	95.3^{o}C

Total load losses of transformer	**11,367 W**
Impedance	**6.24%**
Total weight of transformer	**3774.6 kg**

The following table provides the BOM prepared by the transformer design team. This BOM uses the raw material prices given in section 2.2 of this report, which are derived from the Final Report Preparatory Study (January 2011). These materials are then marked up at the bottom of the table to allow for factory overheads and non-production mark-ups (see section 2.2 of this report). The sum of the raw material costs, labour costs and mark-ups totals to the manufacturer's selling price. This table provides the BOM for 1250 kVA transformer with amorphous material built in a wound core. This transformer has an 11 kV primary with copper wire and 600 V secondary with copper strip.

Table 2-5. Bill of Materials and Labour for 1250 kVA SA1 in a Wound Core (EFF5)

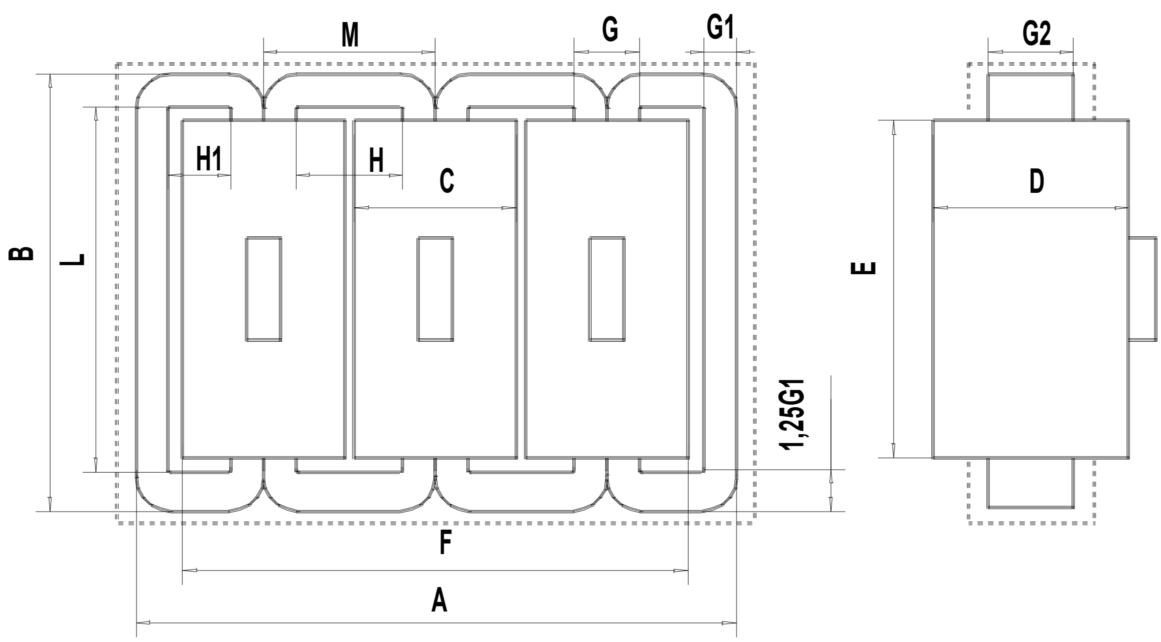
Material item	Type	Quantity	Each	Total
Core material*	Amorphous Core Material	2,222	€ 3.00	€ 6,667
Primary Winding*	Copper wire 3.2x6.0/3.35x6.15mm (kg	594	€ 4.85	€ 2,883
Secondary Winding*	Copper foil 2x (0.7x420) mm (kg)	391	€ 5.05	€ 1,976
Strips for axial canal	resiglass	35	€ 2.54	€ 89
Dielectric*	Resin kg	264	€ 16.82	€ 4,446
Transformer Cabinet	Kilograms	283	€ 0.74	€ 210
High Voltage Terminals	12kV, 100A	3	€ 30.00	€ 90
Low Voltage terminals	1 kV, 1500 A	4	€ 25.00	€ 100
Hardware and Clamps	misc. & nameplate		€ 155.00	€ 155
Scrap factor (applies to items with * above)			1.00%	€ 160
		Total Material Cost		€ 16,775
Labour item	**Description**	**Hours**	**€/hr**	**Total**
Lead Dressing	Prepare leads after winding	0.75	€ 60.00	€ 45
Handling and Slitting	Working with core steel	-	€ 60.00	€ -
Winding the Primary	Varies with N turns	18.99	€ 60.00	€ 1,139
Winding the Secondary	Varies with N turns	4.28	€ 60.00	€ 257
Inspection	Quality assurance check	0.25	€ 60.00	€ 15
Resin Baking windings	Vacuum resin-impregn. process	6.00	€ 60.00	€ 360
Core Assembly	Assemble around coils, varies	3.70	€ 60.00	€ 222
Enclosure Forming and Painting	Manufacture enclosures	6.00	€ 60.00	€ 360
Final Assembly	Clamping winding on core	6.00	€ 60.00	€ 360
Preliminary Test on Windings	Check turns ratio, resistance	0.50	€ 60.00	€ 30
Final Test Assembled unit test	Assembled unit test	0.75	€ 60.00	€ 45
Packing and Pallet Loading	Clamping, wrapping and other	2.00	€ 60.00	€ 120
Marking and Miscellaneous	Labelling bushings, etc.	2.20	€ 60.00	€ 132
		Total Labour Cost		€ 3,085
Manufacturing Cost (Total Material & Total Labour)				€ 19,860
Factory Overhead (Applied to Material Costs Only)		12.5%		€ 2,097
Non-production Cost Markup		25%		€ 5,489
Manufacturer Selling Price				€ 27,446

2.4 EFF7 BOM for 1250 kVA Cast-Coil Dry-Type SA1 in a Wound Core

Main Data

Rated Power	1250 kVA
Rated Voltage	11,000 V ±2x2.5%/600 V
Impedance	6.0%
Winding configuration	Dyn5
Core material	Amorphous ribbon 2605 SA1.
Type of core	Wound, 5 leg

Main dimensions of transformer [mm]



Where:

A = 1793	G1 =99
B = 1278	G2 =396
C = 485	H =322
D = 683	H1 =179
E = 970	L =1055
F =1525	M =520
G = 198	

Data of core

Dimension of main column	198x396 mm
Cross section of main column	658.63 cm^2
Induction in column	1.247 T
Weight of core	2770.8 kg
No-load losses	**528 W**

Primary winding

Turns

Tap	+5.0%	+2.5%	0%	- 2.5%	- 5.0%
Turns	**633**	**618**	**603**	**588**	**573**

Material	Cu
Dimension of wire	4.3x6.0/4.45x6.15mm
Current density	1.469 A/mm^2
Inner Dimensions	386x584 mm
Cooling canal	16 mm
Outer dimensions	485x683 mm
Winding resistance-120^{o}C	1.101 Ώ
Weight of wire of windings	3x287.8 kg
Weight of resin	3x64.7 kg
Weight of strips for axial canal	3x6.6 kg
Load losses	3x1708.4 W
Mean temperature rise	92.4^{o}C

Secondary winding

Turns	19
Material	Cu
Dimension of wire	foil 2x (0.78x450) mm
Current density	1.714 A/mm^2
Inner dimensions	222x420 mm
Cooling canals	2x12 mm
Outer dimensions	316x514 mm
Winding resistance-120^{o}C	0.0009304 Ώ
Weight of windings foil	3x167.5 kg
Weight of resin	3x27.2 kg
Weight of strips for axial canal	3x5.93 kg
Load losses	3x1454.2 W
Mean temperature rise	92.7^{o}C

Total load losses of transformer	**9488 W**
Impedance	**6.26%**
Total weight of transformer	**4753 kg**

The following table provides the BOM prepared by the transformer design team. This BOM uses the raw material prices given in section 2.2 of this report, which are derived from the Final Report Preparatory Study (January 2011). These materials are then marked up at the bottom of the table to allow for factory overheads and non-production mark-ups (see section 2.2 of this report). The sum of the raw material costs, labour costs and mark-ups totals to the manufacturer’s selling price. This table provides the BOM for 1250 kVA

transformer with amorphous material built in a wound core. This transformer has an 11 kV primary with copper wire and 600 V secondary with copper strip.

Table 2-6. Bill of Materials and Labour for 1250 kVA SA1 in a Wound Core (EFF7)

Material item	Type	Quantity	Each	Total
Core material*	Amorphous Core Material	2,771	€ 3.00	€ 8,312
Primary Winding*	Copper wire 4.3x6.0/4.45x6.15mm (kg	843	€ 4.85	€ 4,090
Secondary Winding*	Copper foil 2x (0.78x450) mm (kg)	503	€ 5.05	€ 2,538
Strips for axial canal	resiglass	38	€ 2.54	€ 96
Dielectric*	Resin kg	276	€ 16.82	€ 4,637
Transformer Cabinet	Kilograms	306	€ 0.74	€ 227
High Voltage Terminals	12kV, 100A	3	€ 30.00	€ 90
Low Voltage terminals	1 kV, 1500 A	4	€ 25.00	€ 100
Hardware and Clamps	misc. & nameplate		€ 157.00	€ 157
Scrap factor (applies to items with * above)			1.00%	€ 196
			Total Material Cost	€ 20,443
Labour item	**Description**	**Hours**	**€/hr**	**Total**
Lead Dressing	Prepare leads after winding	0.75	€ 60.00	€ 45
Handling and Slitting	Working with core steel	-	€ 60.00	€ -
Winding the Primary	Varies with N turns	18.99	€ 60.00	€ 1,139
Winding the Secondary	Varies with N turns	4.28	€ 60.00	€ 257
Inspection	Quality assurance check	0.25	€ 60.00	€ 15
Resin Baking windings	Vacuum resin-impregn. process	6.00	€ 60.00	€ 360
Core Assembly	Assemble around coils, varies	4.62	€ 60.00	€ 277
Enclosure Forming and Painting	Manufacture enclosures	6.00	€ 60.00	€ 360
Final Assembly	Clamping winding on core	6.00	€ 60.00	€ 360
Preliminary Test on Windings	Check turns ratio, resistance	0.50	€ 60.00	€ 30
Final Test Assembled unit test	Assembled unit test	0.75	€ 60.00	€ 45
Packing and Pallet Loading	Clamping, wrapping and other	2.00	€ 60.00	€ 120
Marking and Miscellaneous	Labelling bushings, etc.	2.20	€ 60.00	€ 132
			Total Labour Cost	€ 3,140
Manufacturing Cost (Total Material & Total Labour)				€ 23,583
Factory Overhead (Applied to Material Costs Only)		12.5%		€ 2,555
Non-production Cost Markup		25%		€ 6,534
Manufacturer Selling Price				€ 32,672

3 Designs for 2000 kVA Cast-Coil Dry-Type Transformer (BC6)

Basecase Transformer #6 (BC6) represents cast-coil dry-type distributed energy resources (DER) transformers, such as might be found at a wind-turbine site. The rating selected for this basecase is the 2000 kVA three-phase transformer. The following are the technical specifications used as inputs by the design team:

Type: Three-phase, cast-coil, dry-type
KVA: 2000
Primary: 11 kilovolts at 50 Hz
Secondary: 600 volts
Temp Class: 155°C (above ambient, assumed 20°C)
Winding Configuration: Dy5
Cores: a) Silicon steel in mitred stacked core, cruciform, 3-leg
b) Amorphous material in wound core, distributed gap, 5-leg
Taps: +/- 2 x 2.5% above and below the nominal
Impedance: 6%

VITO developed and published a matrix of core and winding losses as a survey tool to facilitate input from manufacturers on the relationship between price and efficiency. The table presented below contains the loss and price information for the 2000 kVA transformer. VITO requested input from manufacturers on the percentage price increase for each of the incremental improvements from the Eff0 transformer. To facilitate a comparison with the Final Report Preparatory Study, CLASP adopted this approach when engaging its design team to prepare the designs presented in this report.

Table 3-1. VITO Survey Tool to Quantify Price Increases Relative to Efficiency, 2000 kVA

BC 6 DER dry-type transformer 2000 kVA		C_0	B_0	A_0	Amorphous
		4000 W	3000 W	2600 W	950 W
		75 dB	70 dB	70 dB	72 dB
B_K	18,000 W	Eff0	Eff1		Eff3
A_K	16,000 W			Eff2	Eff4
Amorphous	13,000 W				Eff5

Thus, there are six transformers that were prepared by CLASP's transformer design team:

a) Stacked cruciform core type step-lap, silicon steel

- Baseline design Eff0: P_0 = 4000 W, P_K = 18,000 W
- Eff1: P_0 = 3000 W, P_K = 18,000 W
- Eff2: P_0 = 2600 W, P_K = 16,000 W

b) Wound 5 legs core, Amorphous, 2605 SA1

- Eff3: P_0 = 950 W, P_K = 18,000 W
- Eff4: P_0 = 950 W, P_K = 16,000 W
- Eff5: P_0 = 950 W, P_K = 13,000 W

The cost of a 2000 kVA increases with improvements in the efficiency, as shown in the table below.

Table 3-2. CLASP Designs Prepared for 2000 kVA Cast-Coil Dry-Type Transformer

	EFF0	EFF1	EFF2	EFF3	EFF4	EFF5
Power rating:	2000	2000	2000	2000	2000	2000
Phases:	3	3	3	3	3	3
Number of legs:	3-leg	3-leg	3-leg	5-leg	5-leg	5-leg
Frequency:	50 Hz	50 Hz	50 Hz	50 Hz	50 Hz	50 Hz
Primary (kilovolts):	11	11	11	11	11	11
Secondary (volts):	600	600	600	600	600	600
Ref. temperature (°C):	120	120	120	120	120	120
Ambient (°C):	20	20	20	20	20	20
Winding Configuration:	Dyn5	Dyn5	Dyn5	Dyn5	Dyn5	Dyn5
Core:	Stacked	Stacked	Stacked	Wound	Wound	Wound
Core Type:	Mitred	Mitred	Mitred	DG	DG	DG
Core Mat'l:	M6	M3 0,27	M-0H	2605 SA1	2605 SA1	2605 SA1
HV Conductor Mat'l:	Cu	Cu	Cu	Cu	Cu	Cu
LV Conductor Mat'l:	Cu	Cu	Cu	Cu	Cu	Cu
Core Losses:	3835	3057	2526	925	927	930
Coil Losses:	18,419	18,637	16,891	18,606	16,367	13,754
Total weight (kg):	3931	4066	4055	5054	5250	5546
Efficiency (100% load):	98.89%	98.92%	99.03%	99.02%	99.14%	99.27%
Selling Price:	€23,584	€23,874	€25,330	€33,406	€34,818	€36,892
% Increase over Eff0:		1%	7%	42%	48%	56%

Four designs were selected from this database of designs for presentation in this chapter of the report, providing detail on the BOM and the performance of the designs. The four designs selected were:

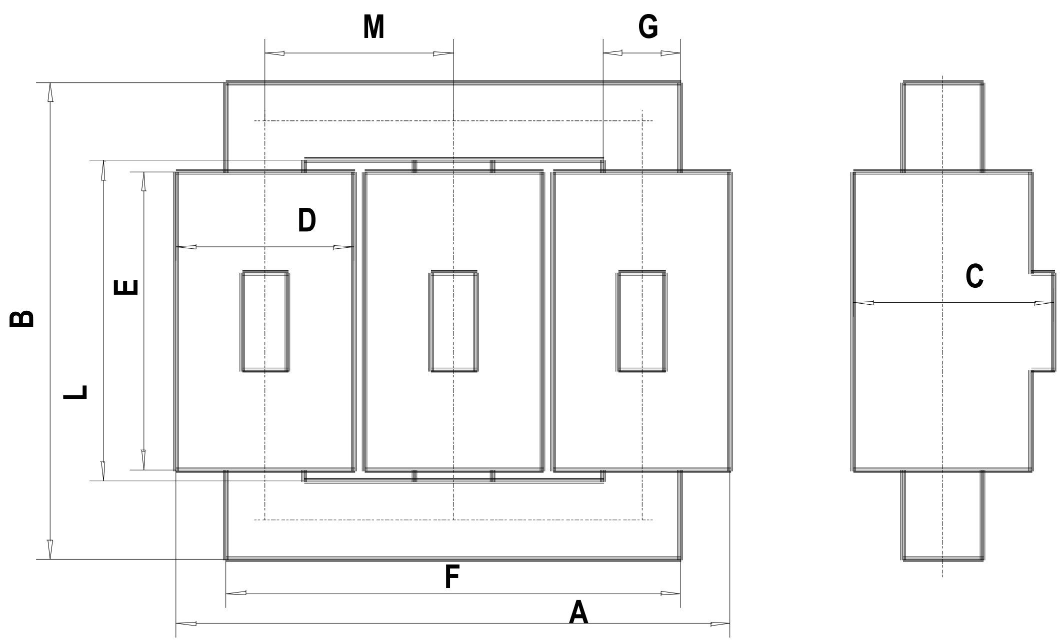
- EFF0 – a 2000 kVA cast-coil transformer built with M6 core steel in a cruciform circular stack, with losses of 3835 W in the core and 18,419 W in the coil at full load.
- EFF2 – a 2000 kVA cast-coil transformer built with H0 (laser-scribed) core steel in a cruciform circular stack, with losses of 2526 W in the core and 16,891 W in the coil at full load.
- EFF4 – a 2000 kVA cast-coil transformer built with amorphous material in a 5-leg wound core configuration, with losses of 927 W in the core and 16,367 W in the coil at full load.
- EFF5 – a 2000 kVA cast-coil transformer built with amorphous material in a 5-leg wound core configuration, with losses of 930 W in the core and 13,754 W in the coil at full load.

3.1 EFF0 BOM for 2000 kVA Cast-Coil Dry-Type M6 in a Cruciform Stack

Main Data

Rated Power	2000 kVA
Rated Voltage	11,000 V ±2x2.5%/600 V
Impedance	6.0%
Winding configuration	Dyn5
Core material	M6
Type of core	Stacked

Main dimensions of transformer [mm]



Where:

A = 1700	F = 1430
B = 1630	G = 275
C = 617	L = 1090
D = 537	M = 580
E = 1020	

Data of core

Diameter of column	275 mm
Cross section of column and yoke	510.9 cm^2
Induction in column	1.697 T
Weight of core	2414.1 kg
No-load losses	**3835 W**

Primary winding

Turns

Tap	+5.0%	+2.5%	0%	- 2.5%	- 5.0%
Turns	600	586	572	558	544

Material	Cu
Dimension of wire	2x(3.15x3.55/3.3x3.7) mm
Current density	2.69 A/mm^2
Inner Diameter	453mm
Cooling canal	16 mm
Outer Diameter	537 mm
Winding resistance-120^{o}C	1.006 Ώ
Weight of wire of windings	3x185.8kg
Weight of resin	3x51.3kg
Weight of strips for axial canal	3x7.03 kg
Load losses	3x3989.3 W

Secondary winding

Turns	18
Material	Cu
Dimension of wire	foil 2x(0.9x490) mm
Current density	2.18 A/mm^2
Inner Diameter	295 mm
Cooling canals	2x12 mm
Outer Diameter	393 mm
Winding resistance-120^{o}C	0.000538 Ώ
Weight of windings foil	3x152.7 kg
Weight of resin	3x 20.7 kg
Weight of strips for axial canal	3x 7.7 kg
Load losses	3x 2150.3 W

Total load losses of transformer	**18,419 W**
Impedance	**6.06%**
Total weight of transformer	**3931 kg**

The following table provides the BOM prepared by the transformer design team. This BOM uses the raw material prices given in section 2.2 of this report, which are derived from the Final Report Preparatory Study (January 2011). These materials are then marked up at the bottom of the table to allow for factory overheads and non-production mark-ups (see section 2.2 of this report). The sum of the raw material costs, labour costs and mark-ups totals to the manufacturer's selling price. This table provides the BOM for 2000 kVA transformer with M6 core steel, built in a cruciform stack. This transformer has an 11 kV primary with copper wire and 600 V secondary with copper strip.

Table 3-3. Bill of Materials and Labour for 2000 kVA M6 in a Cruciform Stack (EFF0)

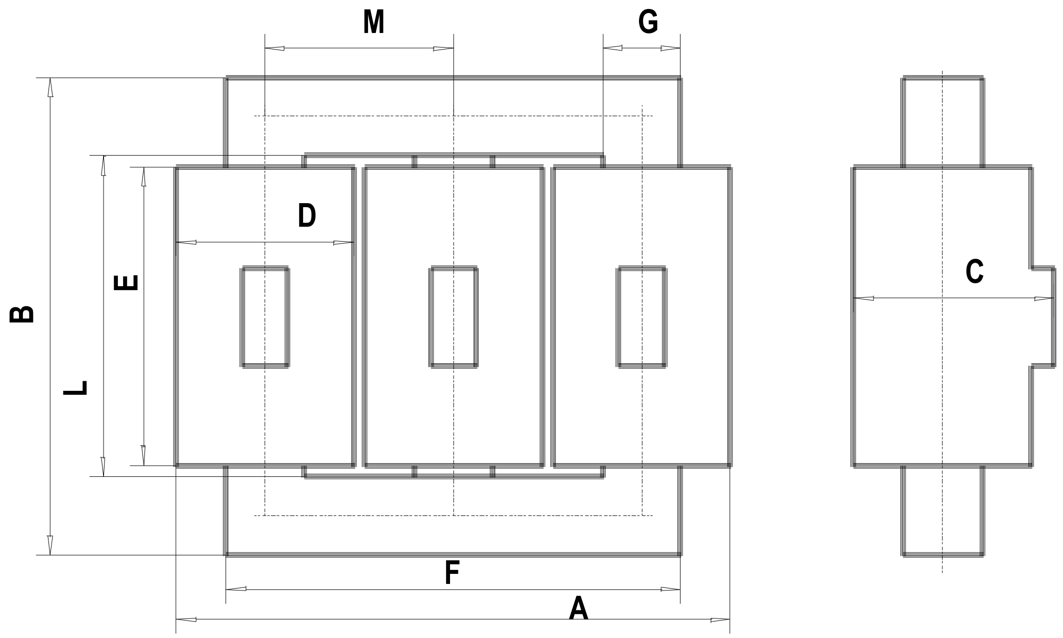
Material item	Type	Quantity	Each	Total
Core material*	M6 Grain-Oriented Silicon Steel	2,414	€ 1.60	€ 3,863
Primary Winding*	Copper wire 2x(3.15x3.55/3.3x3.7) mm	557	€ 4.85	€ 2,703
Secondary Winding*	foil 2x(0.9x490) mm	458	€ 5.05	€ 2,313
Strips for axial canal	resiglass	44	€ 2.54	€ 112
Dielectric*	Resin kg	216	€ 16.82	€ 3,630
Transformer Cabinet	Kilograms	327	€ 0.74	€ 242
High Voltage Terminals	12kV, 100A	3	€ 30.00	€ 90
Low Voltage terminals	1 kV, 1500 A	4	€ 25.00	€ 100
Hardware and Clamps	misc. & nameplate		€ 150.00	€ 150
Scrap factor (applies to items with * above)			1.00%	€ 125
			Total Material Cost	€ 13,328
Labour item	**Description**	**Hours**	**€/hr**	**Total**
Lead Dressing	Prepare leads after winding	1.00	€ 60.00	€ 60
Handling and Slitting	Working with core steel	0.87	€ 60.00	€ 52
Winding the Primary	Varies with N turns	22.50	€ 60.00	€ 1,350
Winding the Secondary	Varies with N turns	6.75	€ 60.00	€ 405
Inspection	Quality assurance check	0.25	€ 60.00	€ 15
Resin Baking windings	Vacuum resin-impregn. process	6.00	€ 60.00	€ 360
Core Assembly	Assemble around coils, varies	9.74	€ 60.00	€ 585
Enclosure Forming and Painting	Manufacture enclosures	6.00	€ 60.00	€ 360
Final Assembly	Clamping winding on core	6.00	€ 60.00	€ 360
Preliminary Test on Windings	Check turns ratio, resistance	0.50	€ 60.00	€ 30
Final Test Assembled unit test	Assembled unit test	0.75	€ 60.00	€ 45
Packing and Pallet Loading	Clamping, wrapping and other	2.00	€ 60.00	€ 120
Marking and Miscellaneous	Labelling bushings, etc.	2.20	€ 60.00	€ 132
			Total Labour Cost	€ 3,874
Manufacturing Cost (Total Material & Total Labour)				€ 17,201
Factory Overhead (Applied to Material Costs Only)		12.5%		€ 1,666
Non-production Cost Markup		25%		€ 4,717
Manufacturer Selling Price				€ 23,584

3.2 EFF2 BOM for 2000 kVA Cast-Coil Dry-Type H0 in a Cruciform Stack

Main Data

Rated Power	2000 kVA
Rated Voltage	11,000 V ±2x2.5%/600 V
Impedance	6.0%
Winding configuration	Dyn5
Core material	M-0H
Type of core	Stacked

Main dimensions of transformer [mm]



Where:

A = 1764	F = 1470
B = 1580	G = 285
C = 644	L = 1040
D = 564	M = 600
E = 970	

Data of core

Diameter of column	285 mm
Cross section of column and yoke	540.1cm^2
Induction in column	1.7 T
Weight of core	2521 kg
No-load losses	**2526 W**

Primary winding

Turns

Tap	**+5.0%**	**+2.5%**	**0%**	**- 2.5%**	**- 5.0%**
Turns	566	553	540	527	514

Material	Cu
Dimension of wire	4.0x6.0/4.15x6.15 mm
Current density	2.525 A/mm^2
Inner Diameter	474 mm
Cooling canal	14 mm
Outer Diameter	566 mm
Winding resistance-120°C	0.909 Ω
Weight of wire of windings	3x197.5 kg
Weight of resin	3x43.6 kg
Weight of strips for axial canal	3x7.7 kg
Load losses	3x3604.7 W
Mean temperature rise	95.7 °C

Secondary winding

Turns	17
Material	Cu
Dimension of wire	foil 2x(1.0x450) mm
Current density	2.138 A/mm^2
Inner Diameter	297 mm
Cooling canals	2x 14 mm
Outer Diameter	404 mm
Winding resistance-120°C	0.0005069 Ω
Weight of windings foil	3x149.9 kg
Weight of resin	3x20.8 kg
Weight of strips for axial canal	3x 7.7 kg
Load losses	3x2027.7 W
Mean winding temperature rise	99.3 °C

Total load losses of transformer	**16,891 W**
Impedance	6.38%
Total weight of transformer	**4055 kg**

The following table provides the BOM prepared by the transformer design team. This BOM uses the raw material prices given in section 2.2 of this report, which are derived from the Final Report Preparatory Study (January 2011). These materials are then marked up at the bottom of the table to allow for factory overheads and non-production mark-ups (see section 2.2 of this report). The sum of the raw material costs, labour costs and mark-ups totals to the manufacturer's selling price. This table provides the BOM for 2000 kVA transformer with H0 core steel, built in a cruciform stack. This transformer has an 11 kV primary with copper wire and 600 V secondary with copper strip.

Table 3-4. Bill of Materials and Labour for 2000 kVA M-OH in a Cruciform Stack (EFF2)

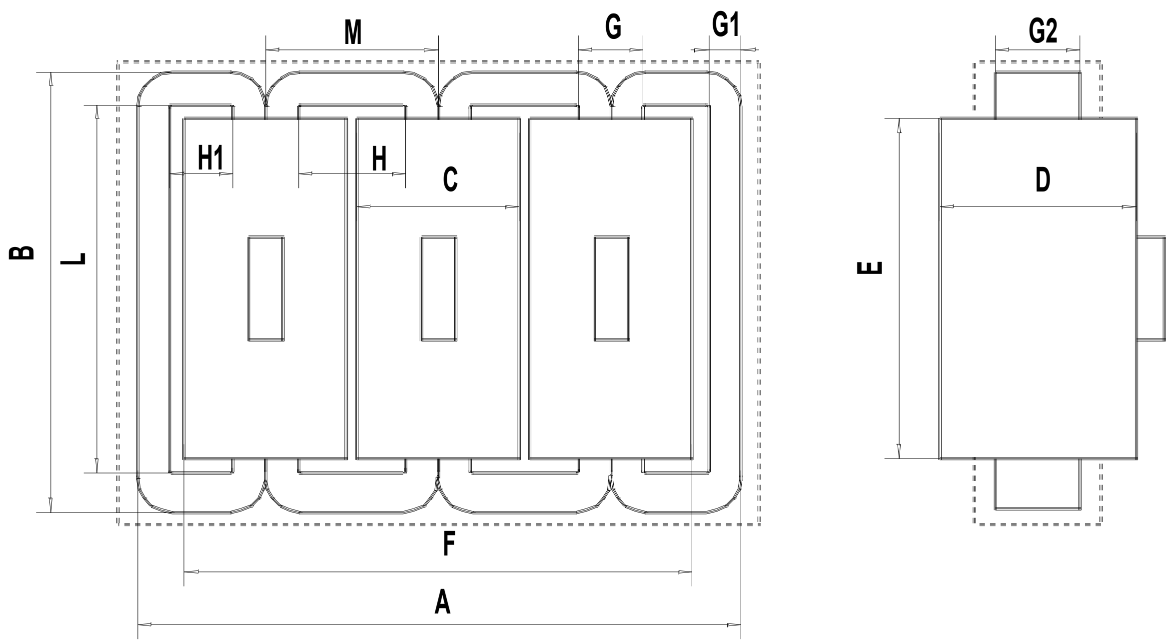
Material item	Type	Quantity	Each		Total	
Core material*	M-0H Laser-Scribed Silicon Steel	2,521	€	1.81	€	4,563
Primary Winding*	Copper wire 4.0x6.0/4.15x6.15 mm	593	€	4.85	€	2,874
Secondary Winding*	Copper foil 2x(1.0x450) mm	450	€	5.05	€	2,271
Strips for axial canal	resiglass	46	€	2.54	€	117
Dielectric*	Resin kg	194	€	16.82	€	3,256
Transformer Cabinet	Kilograms	332	€	0.74	€	246
High Voltage Terminals	12kV, 100A	3	€	30.00	€	90
Low Voltage terminals	1 kV, 1500 A	4	€	25.00	€	100
Hardware and Clamps	misc. & nameplate		€	152.00	€	152
Scrap factor (applies to items with * above)				1.00%	€	130
		Total Material Cost			€	13,799
Labour item	**Description**	**Hours**	**€/hr**		**Total**	
Lead Dressing	Prepare leads after winding	1.00	€	60.00	€	60
Handling and Slitting	Working with core steel	0.85	€	60.00	€	51
Winding the Primary	Varies with N turns	21.23	€	60.00	€	1,274
Winding the Secondary	Varies with N turns	6.38	€	60.00	€	383
Inspection	Quality assurance check	0.25	€	60.00	€	15
Resin Baking windings	Vacuum resin-impregn. process	6.00	€	60.00	€	360
Core Assembly	Assemble around coils, varies	10.10	€	60.00	€	606
Enclosure Forming and Painting	Manufacture enclosures	6.00	€	60.00	€	360
Final Assembly	Clamping winding on core	6.00	€	60.00	€	360
Preliminary Test on Windings	Check turns ratio, resistance	0.50	€	60.00	€	30
Final Test Assembled unit test	Assembled unit test	0.75	€	60.00	€	45
Packing and Pallet Loading	Clamping, wrapping and other	2.00	€	60.00	€	120
Marking and Miscellaneous	Labelling bushings, etc.	2.20	€	60.00	€	132
		Total Labour Cost			€	3,795
Manufacturing Cost (Total Material & Total Labour)					€	17,594
Factory Overhead (Applied to Material Costs Only)		12.5%			€	1,725
Non-production Cost Markup		25%			€	4,830
Manufacturer Selling Price					€	24,149

3.3 EFF4 BOM for 2000 kVA Cast-Coil Dry-Type SA1 in a Wound Core

Main Data

Rated Power	2000 kVA
Rated Voltage	11,000 V ±2x2.5%/600 V
Impedance	6.0%
Winding configuration	Dyn5
Core material	Amorphous 2605 SA1
Type of core	Wound

Main dimensions of transformer [mm]



Where:

A = 1840	G1 = 102.5
B = 1390	G2 = 409
C = 499	H = 323
D = 703	H1 = 179
E =1070	L = 1160
F = 1566	M = 534
G = 205	

Data of core

Dimensions of column	205x409 mm
Cross section of column and yoke	704.3 cm^2
Induction in column	1.481 T
Weight of core	3189 kg
No-load losses	**927 W**

Primary winding

Turns

Tap	+5.0%	+2.5%	0%	- 2.5%	- 5.0%
Turns	500	488	476	464	452

Material	Cu
Dimension of wire	2*(2.5x5.6/2.65x5.75) mm
Current density	2.164 A/mm^2
Inner Dimensions	409x613 mm
Cooling canal	16 mm
Outer Dimensions	499x703 mm
Winding resistance-120^{o}C	0.832 Ώ
Weight of wire of windings	3x250.4kg
Weight of resin	3x66.5 kg
Weight of strips for axial canal	3x9.7 kg
Load losses	3x3299.6 W
Mean temperature rise	93.9 ^{o}C

Secondary winding

Turns	15
Material	Cu
Dimension of wire	foil 2x(1.0x500) mm
Current density	1.925 A/mm^2
Inner Dimensions	229x433 mm
Cooling canals	2x16 mm
Outer Dimensions	339x543 mm
Winding resistance-120^{o}C	0.000539 Ώ
Weight of windings foil	3x196.9 kg
Weight of resin	3x26.6 kg
Weight of strips for axial canal	3x 8.3 kg
Load losses	3x2156 W
Mean winding temperature rise	91.5 ^{o}C

Total load losses of transformer	**16,367 W**
Impedance	**5.96%**
Total weight of transformer	**5250 kg**

The following table provides the BOM prepared by the transformer design team. This BOM uses the raw material prices given in section 2.2 of this report, which are derived from the Final Report Preparatory Study (January 2011). These materials are then marked up at the bottom of the table to allow for factory overheads and non-production mark-ups (see section 2.2 of this report). The sum of the raw material costs, labour costs and mark-ups totals to the manufacturer's selling price. This table provides the BOM for 2000 kVA

transformer with amorphous material built in a wound core. This transformer has an 11 kV primary with copper wire and 600 V secondary with copper strip.

Table 3-5. Bill of Materials and Labour for 2000 kVA SA1 in a Wound Core (EFF4)

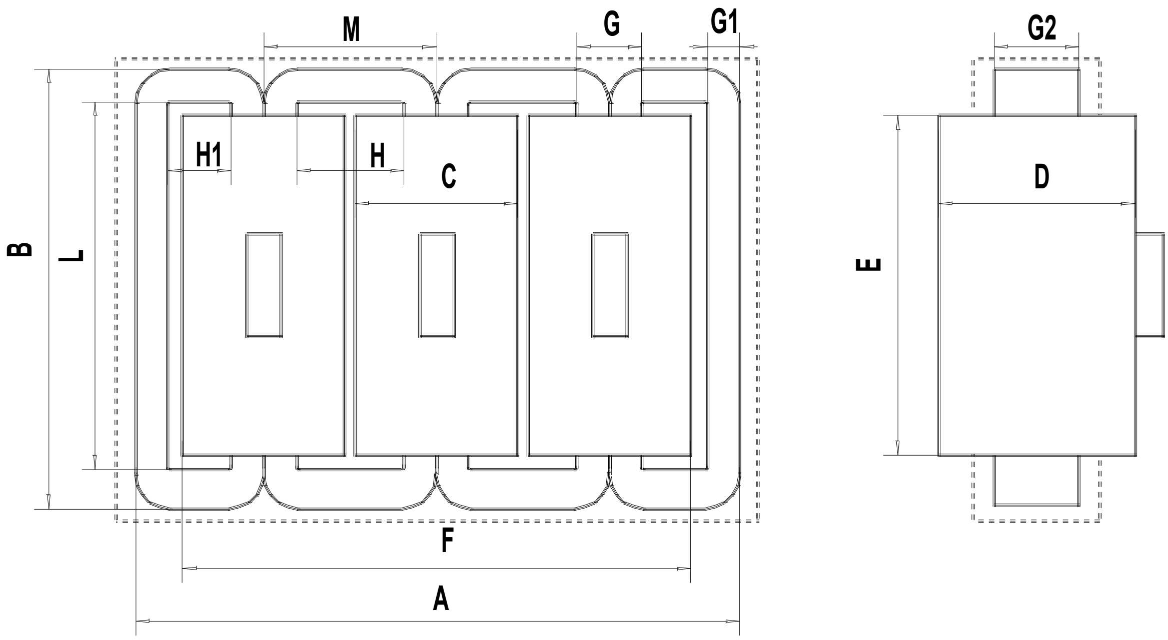
Material item	Type	Quantity	Each	Total
Core material*	Amorphous Core Material	3,189	€ 3.00	€ 9,567
Primary Winding*	Copper wire 2*(2.5x5.6/2.65x5.75) mm	751	€ 4.85	€ 3,643
Secondary Winding*	Copper foil 2x(1.0x500) mm	591	€ 5.05	€ 2,984
Strips for axial canal	resiglass	55	€ 2.54	€ 140
Dielectric*	Resin kg	281	€ 16.82	€ 4,728
Transformer Cabinet	Kilograms	329	€ 0.74	€ 244
High Voltage Terminals	12kV, 100A	3	€ 30.00	€ 90
Low Voltage terminals	1 kV, 1500 A	4	€ 25.00	€ 100
Hardware and Clamps	misc. & nameplate		€ 154.00	€ 154
Scrap factor (applies to items with * above)			1.00%	€ 209
		Total Material Cost		€ 21,858
Labour item	**Description**	**Hours**	**€/hr**	**Total**
Lead Dressing	Prepare leads after winding	1.00	€ 60.00	€ 60
Handling and Slitting	Working with core steel	-	€ 60.00	€ -
Winding the Primary	Varies with N turns	18.75	€ 60.00	€ 1,125
Winding the Secondary	Varies with N turns	5.63	€ 60.00	€ 338
Inspection	Quality assurance check	0.25	€ 60.00	€ 15
Resin Baking windings	Vacuum resin-impregn. process	6.00	€ 60.00	€ 360
Core Assembly	Assemble around coils, varies	5.32	€ 60.00	€ 319
Enclosure Forming and Painting	Manufacture enclosures	6.00	€ 60.00	€ 360
Final Assembly	Clamping winding on core	6.00	€ 60.00	€ 360
Preliminary Test on Windings	Check turns ratio, resistance	0.50	€ 60.00	€ 30
Final Test Assembled unit test	Assembled unit test	0.75	€ 60.00	€ 45
Packing and Pallet Loading	Clamping, wrapping and other	2.00	€ 60.00	€ 120
Marking and Miscellaneous	Labelling bushings, etc.	2.20	€ 60.00	€ 132
		Total Labour Cost		€ 3,263
Manufacturing Cost (Total Material & Total Labour)				€ 25,122
Factory Overhead (Applied to Material Costs Only)		12.5%		€ 2,732
Non-production Cost Markup		25%		€ 6,964
Manufacturer Selling Price				€ 34,818

3.4 EFF5 BOM for 2000 kVA Cast-Coil Dry-Type SA1 in a Wound Core

Main Data

Rated Power	2000 kVA
Rated Voltage	11,000 V ±2x2.5%/600 V
Impedance	6.0%
Winding configuration	Dyn5
Core material	Amorphous 2605 SA1
Type of core	Wound

Main dimensions of transformer [mm]



Where:

A = 1858	G1 = 102.5
B = 1390	G2 = 409
C = 505	H = 325
D = 709	H1 = 185
E =1070	L = 1160
F = 1584	M = 540
G = 205	

Data of core

Dimensions of column	205x409 mm
Cross section of column and yoke	704.3 cm^2
Induction in column	1.481 T
Weight of core	3197 kg
No-load losses	**927 W**

Primary winding

Turns

Tap	**+5.0%**	**+2.5%**	**0%**	**- 2.5%**	**- 5.0%**
Turns	500	488	476	464	452

Material	Cu
Dimension of wire	2*(2.8x6.0/2.95x6.15) mm
Current density	1.804 A/mm^2
Inner Dimensions	415x619 mm
Cooling canal	16 mm
Outer Dimensions	505x709 mm
Winding resistance-120^{o}C	0.700 Ώ
Weight of wire of windings	3x303.2 kg
Weight of resin	3x67.6 kg
Weight of strips for axial canal	3x10.5 kg
Load losses	3x2776.3 W
Mean temperature rise	88.6 ^{o}C

Secondary winding

Turns	15
Material	Cu
Dimension of wire	foil 2x(1.2x500) mm
Current density	1.604 A/mm^2
Inner Dimensions	229x433 mm
Cooling canals	2x16 mm
Outer Dimensions	345x549 mm
Winding resistance-120^{o}C	0.000452 Ώ
Weight of windings foil	3x237.8 kg
Weight of resin	3x26.8 kg
Weight of strips for axial canal	3x 8.7 kg
Load losses	3x1808.3 W
Mean winding temperature rise	89.1 ^{o}C

Total load losses of transformer	**13,754 W**
Impedance	6.06%
Total weight of transformer	**5546 kg**

The following table provides the BOM prepared by the transformer design team. This BOM uses the raw material prices given in section 2.2 of this report, which are derived from the Final Report Preparatory Study (January 2011). These materials are then marked up at the bottom of the table to allow for factory overheads and non-production mark-ups (see section 2.2 of this report). The sum of the raw material costs, labour costs and mark-ups

totals to the manufacturer's selling price. This table provides the BOM for 2000 kVA transformer with amorphous material built in a wound core. This transformer has an 11 kV primary with copper wire and 600 V secondary with copper strip.

Table 3-6. Bill of Materials and Labour for 2000 kVA SA1 in a Wound Core (EFF5)

Material item	Type	Quantity	Each	Total
Core material*	Amorphous Core Material	3,197	€ 3.00	€ 9,591
Primary Winding*	Copper wire 4.3x6.0/4.45x6.15mm (kg)	910	€ 4.85	€ 4,412
Secondary Winding*	Copper foil 2x (0.78x450) mm (kg)	714	€ 5.05	€ 3,603
Strips for axial canal	resiglass	58	€ 2.54	€ 147
Dielectric*	Resin kg	283	€ 16.82	€ 4,765
Transformer Cabinet	Kilograms	332	€ 0.74	€ 246
High Voltage Terminals	12kV, 100A	3	€ 30.00	€ 90
Low Voltage terminals	1 kV, 1500 A	4	€ 25.00	€ 100
Hardware and Clamps	misc. & nameplate		€ 155.00	€ 155
Scrap factor (applies to items with * above)			1.00%	€ 224
		Total Material Cost		€ 23,333
Labour item	**Description**	**Hours**	**€/hr**	**Total**
Lead Dressing	Prepare leads after winding	1.00	€ 60.00	€ 60
Handling and Slitting	Working with core steel	-	€ 60.00	€ -
Winding the Primary	Varies with N turns	18.75	€ 60.00	€ 1,125
Winding the Secondary	Varies with N turns	5.63	€ 60.00	€ 338
Inspection	Quality assurance check	0.25	€ 60.00	€ 15
Resin Baking windings	Vacuum resin-impregn. process	6.00	€ 60.00	€ 360
Core Assembly	Assemble around coils, varies	5.33	€ 60.00	€ 320
Enclosure Forming and Painting	Manufacture enclosures	6.00	€ 60.00	€ 360
Final Assembly	Clamping winding on core	6.00	€ 60.00	€ 360
Preliminary Test on Windings	Check turns ratio, resistance	0.50	€ 60.00	€ 30
Final Test Assembled unit test	Assembled unit test	0.75	€ 60.00	€ 45
Packing and Pallet Loading	Clamping, wrapping and other	2.00	€ 60.00	€ 120
Marking and Miscellaneous	Labelling bushings, etc.	2.20	€ 60.00	€ 132
		Total Labour Cost		€ 3,264
Manufacturing Cost (Total Material & Total Labour)				€ 26,597
Factory Overhead (Applied to Material Costs Only)		12.5%		€ 2,917
Non-production Cost Markup		25%		€ 7,378
Manufacturer Selling Price				€ 36,892

4 Methodology and Inputs

In support of the European Commission's analysis of Distribution and Power Transformers, CLASP has undertaken two studies on the relationship between manufacturer's selling price and efficiency covering five of the seven base case transformers evaluated by the Commission. In August 2010, CLASP published a design report on three oil-immersed transformers:

- 400 kVA oil-immersed three-phase unit, representing distribution transformers
- 1000 kVA oil-immersed three-phase unit, representing industry transformers
- 2000 kVA oil-immersed three-phase unit, representing distributed energy resources (DER) transformers

In this report, CLASP is publishing design results on two cast-coil dry-type transformers:

- 1250 kVA cast-coil dry-type three-phase unit, representing industry transformers
- 2000 kVA cast-coil dry-type three-phase unit, representing distributed energy resources (DER) transformers

Understanding how the price of transformers increases as the efficiency improves is important because it enables an accurate assessment of life-cycle costs and associated payback periods. Generally, a transformer becomes more expensive as efficiency improves because it is incorporating either more material and/or better quality materials.

CLASP commissioned the development of 15 transformer designs spanning a range of efficiency levels for these two cast-coil dry-type transformers. In each case, both stacked core and wound core designs were prepared, the stacked cores use grain-oriented electrical steel and the wound core designs use amorphous material.

The designs were based initially on a baseline unit, typically constructed with M6 core steel, a copper primary and secondary. Materials would then be substituted that would improve the efficiency, such as better core steels (e.g., M3, laser-scribed domain-refined (M-OH), and amorphous (SA1)) and lower loss designs.

4.1 Methodology Followed

For the two base case models, this analysis explored the relationship between the manufacturer selling prices and corresponding transformer efficiencies. To prepare these designs, CLASP contracted Ivo Pinkiewicz and Janusz Ostrowski from Poland, each of whom have more than two decades of experience designing and manufacturing transformers in Poland.

Using a range of input parameters and material prices, the design team prepared cost-optimised designs with the core and coil losses and impedance specified in the Preparatory Study. This design files prepared for each of the fifteen designs have specific information about the core and coil, including physical characteristics, dimensions, material requirements and mechanical clearances, as well as a complete electrical analysis of the final design. This output is then used to generate an estimated cost of manufacturing materials and labour, which is then converted to a manufacturer's selling price by applying mark-ups on direct costs.

4.1.1 Design Team Member: Ivo Pinkiewicz

Ivo Pinkiewicz was born in 1938 in Lublin, Poland. He obtained his Dipl. Eng. and M.Sc. in Electrical Engineering at the Technical University, Lodz in 1961, and his D.Sc. in Electrical Engineering at the Electro-Technical Institute, Warsaw in 1977.

From 1961 to 1965, Dr. Pinkiewicz was a test engineer at the Transformer Test Station in Transformer factory ELTA in Lodz. From 1965 to 1982 he was the Head of High Current Laboratory in the Transformer Division of Electro-Technical Institute in Warsaw. From 1982 to 1991 he was the Manager of the Technology Department in the Transformer Division, Lodz of Institute of Power Engineering, Warsaw. From 1991 to 2002, he was the manager of the Transformer Division, Lodz of Institute of Power Engineering in Warsaw.

Dr. Pinkiewicz's special fields of experience include engineering, development and testing of power and distribution transformers; and quality management and diagnostics of power transformers. He serves as the chairman of the Polish TC 79 Power Transformers of PKN (IEC TC14, CENELEC TC14) and is a distinguished member of the International Council on Large Electric Systems (CIGRE, Conseil Internationale des Grands Réseaux Électriques).

4.1.2 Design Team Member: Janusz Ostrowski

Janusz Ostrowski was born in 1950 in Lodz, Poland. He obtained his Dipl. Eng. and M.Sc. in Electrical Engineering at the Technical University, Lodz in 1973. From 1973 to 1999, Mr. Ostrowski worked as a design engineer at Design Department in the Transformer Division, Lodz of the Institute of Power Engineering in Warsaw. From 1999 to 2002 he was made Head of the Design Department in the Transformer Division, Lodz of the Institute of Power Engineering, Warsaw. Starting in 2007, Mr. Ostrowski worked as Head of the Design Department at the Transformer Factory in Zychlin, Poland.

Mr. Ostrowski's special fields of experience include optimisation of distribution transformer design and computer transformer design in general.

4.2 Cast Coils

Cast coil transformers can be made in both a stacked core configuration (more typical) and a wound core configuration (for amorphous designs). The critical differentiating factor for cast coil transformers is that the electrical windings are encased (i.e., cast) into an epoxy resin, which binds them permanently, improves short-circuit strength and protects the windings and insulation from exposure to contaminants. The encapsulation process must be carried out and under strict environmental control. After preparing the windings on the lathe, they are put through a preheating oven and kept inside until the casting mould temperature reaches the encapsulation temperature. A resin mix is prepared and the preheated coils are moved to a vacuum casting chamber. Once the vacuum in the chamber has been reached, resin is poured into the moulds. The resin viscosity is very low when poured into the moulds, filling voids. After casting is finished, the coils are moved to a curing oven where they resin compound is cured and achieves its final properties. The figure on the right shows a partially assembled, cast-coil transformer, where the cast epoxy is coloured red. These are the cylinders which contain the windings, and the terminal connection points are located on the front of the cast coils.

Figure 4-1. Picture of a Three-Phase Cast-Coil Dry-Type Transformer

The figure on the following page shows the primary and secondary winding cast-coils, the core steel, mounting hardware and electrical connections. This illustration is included here, as it provides an excellent depiction of a cast-coil transformer and how it is physically constructed. The illustration is reproduced from a marketing brochure from Hyosung Corporation in Korea.

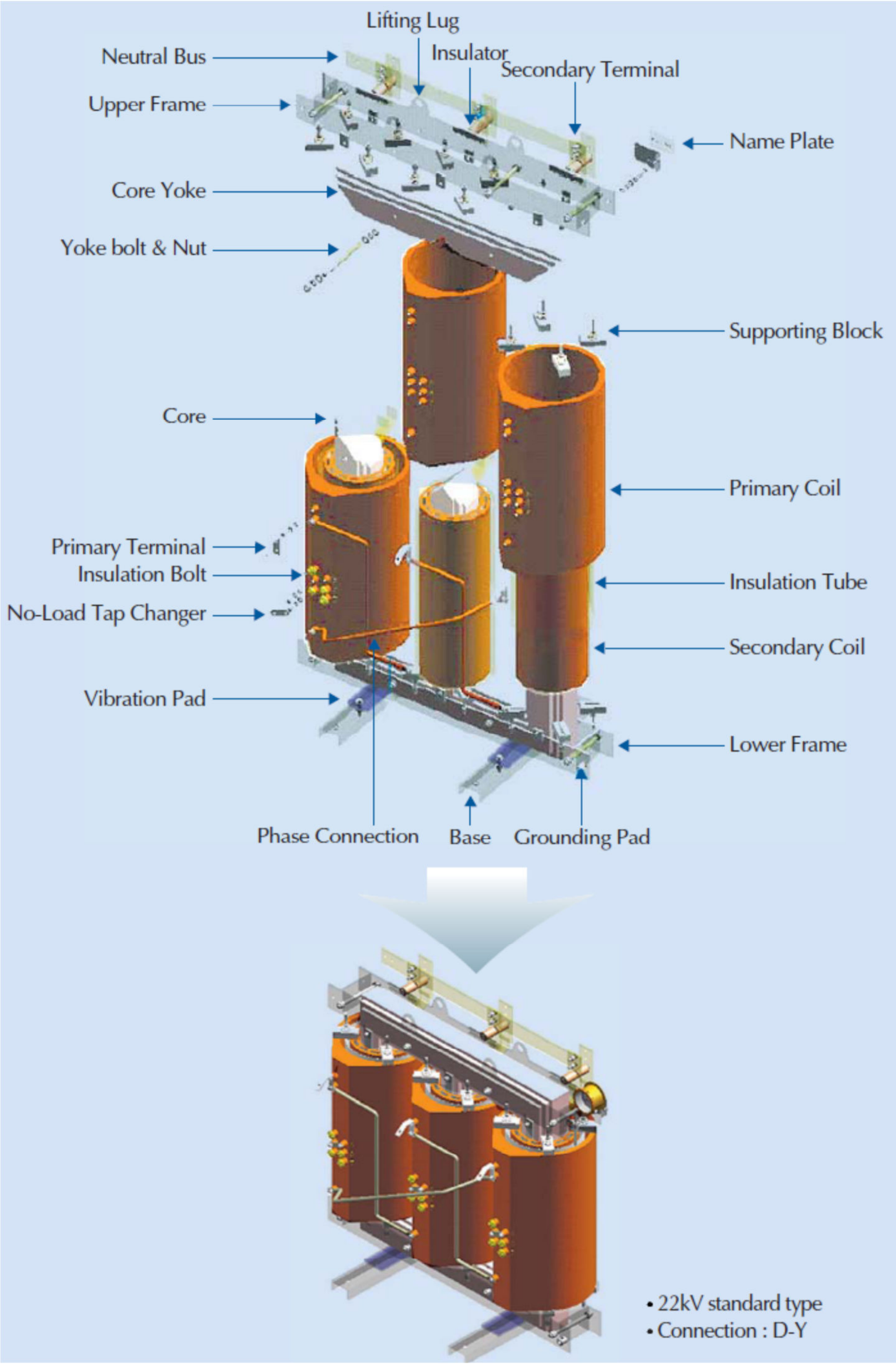


Figure 4-2. Diagram Depicting Assembly of a Cast-Coil Dry-Type Transformer

Source: Hyosung Corporation. www.hyosungpni.co.kr/common/file/download.do?seq=5187

4.3 Input Assumptions

In preparing the designs, the design team used three different grain-oriented electrical steels as well as amorphous material. The table below provides the thickness and performance information for these steels. As the improved grades of steel are used, the watts of energy lost per pound of core steel decrease. The measurement of watts per pound of core steel is presented at 50 Hz for fixed levels of magnetic flux – 1.3, 1.5 and 1.7 Tesla.

Table 4-1. Core Steels Used to Improve the Efficiency of the Cast-Coil Transformers

Steel	Thickness (mm)	Losses per Pound (Watts/kg)	Description
M6	0.35	1.00 W/kg at 1.5 T 1.45 W/kg at 1.7 T	Grain-oriented silicon steel
M3	0.27	0.82 W/kg at 1.5 T 1.20 W/kg at 1.7 T	Grain-oriented silicon steel
H-0 DR	0.23	0.93 W/kg at 1.7 T	"Domain-refined, high permeability" grade silicon steel, laser-scribed
SA1	0.025	0.208 W/kg at 1.3 T	Amorphous core steel (silicon and boron); flux density limitation - testing at 1.3 T

Source: Grain-Oriented Electrical Steel Sheets, Nippon Steel Corporation, 2004.

The following table presents the prices of materials used in transformer manufacturing. These prices were derived from five-year averages that were developed for the North American market as part of the US Department of Energy regulatory analysis of distribution transformers published in October 2007. The prices below were published in VITO's Final Report Preparatory Study published in January 2011 and the values reflect an adaptation of the US DOE material prices with correction/input from European transformer manufacturers. The prices are presented in two columns: the price that manufacturers pay for the material (i.e., the business-to-business cost), and the marked-up price representing what the material is worth when the transformer manufacturer sells the transformer to a customer. When running the design optimisation programme, the marked-up prices are used, however when preparing an estimate of the cost of manufacture, the non-marked up prices are used. This material prices are shown in the Bill of Material (BOM) presented in chapters 3 and 4 of this study.

It should also be noted that the table in the Preparatory Study provides a range of prices for amorphous material, specifically €2.50-3.61/kg. For the purposes of the analysis conducted by the CLASP design team, a price of €3.00/kg was used. Finally, two material prices were needed which did not appear in the Preparatory Study table, specifically the cost of the casting resin, for which CLASP used €16.82/kg and strips for the axial channels €2.54/kg.

Table 4-2. Material Prices Published in Chapter 2 of Preparatory Study (January 2011)

Dry-type transformers	2002-2006 average 5 year material price in €/kg	2002-2006 average 5 year marked-up material price in €/kg
Domain refined core steel	2.14	3.11
M3 core steel	1.81	2.6
M4 core steel	1.72	2.48
M5 core steel	1.64	2.36
M6 core steel	1.6	2.31
M19 core steel (26 gauge)	1.03	1.49
M36 core steel (29 gauge)	0.95	1.35
M36 core steel (26 gauge)	0.86	1.25
M43 core steel (26 gauge)	0.81	1.18
Rectangular copper wire 0.1 x 0.2. Nomex	4.85	6.99
Rectangular aluminium wire 0.1 x 0.2. Nomex	3.48	5.03
Copper strip. thickness range 0.20-0.045	5.05	7.28
Aluminium strip. thickness range 0.20-0.045	2.87	4.14
Nomex insulation	30.64	44.16
Cequin insulation	18.7	26.95
Impregnation (per litre)	3.71	5.22
Winding combs	31.36	44.11
Enclosure steel *	~~15.99~~ / 0.74	~~23.07~~ / 1.08
Amorphous – finished core, volume	2.5-3.61	5.17

* The cost per kilogram for enclosure steel published in the January 2011 VITO Preparatory Study seemed unusually high. The five year average was shown as being €15.99 per kilogram. Therefore, the enclosure cost estimates generated for this analysis are based on applying the oil-immersed tank steel price of €0.74 per kilogram. Marked-up, the enclosure steel price is €1.08 per kilogram.

Although they are based on data from the United States, the mark-ups used in this table were also applied to the raw material costs in this analysis of European transformers. The manufacturer’s selling price is equal to the full production cost, which is a combination of direct labour, direct materials, and overhead plus the non-production costs. The overheads contributing to full production cost includes indirect labour, indirect material, maintenance, depreciation, taxes, and insurance related to company assets. Non-production costs include the cost of selling (market research, advertising, sales representatives, logistics), general and administrative costs, research and development (R&D), interest payments, and profit.

In its analysis published in September 2007, the US Department of Energy used a series of mark-ups that were intended to represent reasonable averages for the transformer manufacturing industry. The following mark-ups resulted:

- Scrap and handling factor: 2.5% mark-up. This mark-up applies to variable materials (e.g., core steel, windings, insulation). It accounts for the handling of material (loading into assembly or winding equipment) and the scrap material that cannot be used in the production of a finished transformer (e.g., lengths of wire too short to wind, trimmed core steel). Material handling is tracked as labour and represents 1.5% of the material and the scrap is calculated as material and is calculated as 1% of the material.

- Factory overhead: 12.5% mark-up. Factory overhead includes all the indirect costs associated with production, indirect materials and energy use (e.g., annealing furnace), taxes, and insurance. Factory overhead is only applied to the direct material production costs.

- Non-production: 25% mark-up. This mark-up reflects costs including selling, general and administrative, R&D, interest payments, and profit factor. The Department applied the non-production mark-up to the sum of direct material, direct labour, and factory overhead.

The application of these mark-ups can be found in the BOM tables presented in Chapters 2 and 3 of this report.