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WHITEPAPER

MAXIMIZING DISTRIBUTION TRANSFORMER RESOURCE-EFFICIENCY

POTENTIAL CONTRIBUTION TO EU GREEN DEAL OBJECTIVES

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Executive summary

With the *Green Deal* from December 2019 and the *Circular Economy Action Plan* from March 2020, the EU strongly commits to improving both energy efficiency and material efficiency. In electrical applications it is not always apparent how a trade-off between these goals can be avoided. The sustainable peak load concept for public distribution transformers does exactly that: it is beneficial to transformer energy efficiency as well as material efficiency, with no need for compromise.

At the origin of the concept lies the fact that many public distribution transformers, as currently rated, are underexploited. This has historical antecedents. Stringent rules on loss reduction, compactness, and absence of toxic substances prompted various technological innovations, including the use of highly conductive material for the windings, magnetic steel with reduced losses, thermally upgraded paper as a solid insulation, and the use of natural ester as a liquid insulation. As a result, transformers can withstand higher temperatures in the windings, and consequently higher peak demand, without compromising unit reliability or lifetime. This potential is usually not exploited.

In the sustainable peak load transformer concept, the unit complies with the energy performance requirements for a transformer of its size (e.g. requirements for a 400 kVA unit), but is allowed to be subject to temporary peak load values that are higher than usual (e.g. peak loads up to 540 kVA).

A group of experts conducted a modelling exercise to assess the impact of selecting sustainable peak load units for all transformer replacements in public distribution networks in the EU, with the following findings:

- The total annual energy losses of a sustainable peak load unit are similar to those of a conventional unit. This is due to the fact that the average loading in public distribution networks is low, resulting in a higher relative importance of no-load losses compared to load losses.

- The material savings potential of sustainable peak load transformers is substantial, with reductions in total weight of 11 - 15%.

- The purchase cost of a sustainable peak load transformer is comparable to that of a conventional transformer if all other parameters are kept the same.

Given these conclusions, widespread application of the sustainable peak load concept in EU public distribution networks is recommended. It would maximize both the energy efficiency and the material efficiency of public distribution transformers.

A major economic advantage of the sustainable peak load transformer is its compactness. Due to the transition away from fossil fuels, substantial growth in electricity consumption is expected in some sectors supplied by distribution networks. The sustainable peak load transformer provides the opportunity to upgrade transformer peak power while keeping the same unit dimensions, saving in installation costs. This will mean that such upgrades can be made at an earlier stage, making the distribution grid more robust.

WHY DOES IT MATTER?

The ambition set out in the European Green Deal in December 2019 requires that all technically and economically feasible avenues to decarbonisation be rolled out rigorously. Maximizing the energy performance of electrical distribution networks is one of these avenues. At the same time, the European Green Deal also expressed the ambition of making the economy more material efficient, resulting in the Circular Economy Action Plan. In the area of electrical energy there is an inherent conflict between these twin ambitions, since a key measure for improving the energy efficiency of electrical systems is increasing the amount of conductor material. Making smart use of electrical systems can in some cases mitigate this trade-off.

The ***sustainable peak load concept*** deployed in distribution transformers represents such a smart solution. It does not change the transformers themselves, but instead maximizes their output for material efficiency without compromising their energy performance. It can be applied in all cases where the difference between peak and average demand is proportionately high, which is usually the case in public distribution networks.

SCOPE: PUBLIC DISTRIBUTION TRANSFORMERS

This whitepaper focuses on medium-power transformers in general and on public distribution transformers in particular. There were an estimated 2.25 million such units (400 kVA equivalent) in the EU in 2005 [1].

For deployment of the sustainable peak load concept to be feasible, the load factor must be relatively low. The Transformer Ecodesign Preparatory Study of 2011 assumed a load factor of 0.15 for distribution networks, a figure which is based on the assessment of various data from different countries [2, p. 151]. Although this figure might initially seem low, it can be explained by the need for redundancy and reliability in public electricity networks, and the need to design the system to handle peak rather than average demand. The network needs to withstand occasional simultaneous load switching. It also needs to have redundancy to cope with component failure and emergency conditions, and it should anticipate the growing demand for electricity. This low load factor, combined with the fact that they all have liquid insulation, makes public distribution transformers ideal candidates for the sustainable peak load concept.

That said, there is no constraint from using the same concept for medium-power transformers connecting distributed energy resources (DER) or liquid-immersed industrial transformers with a similar peaky demand profile.

MINIMUM ENERGY PERFORMANCE STANDARDS

The Ecodesign regulation on transformers sets out minimum energy performance requirements for medium-power transformers. Table I.1 applies to three-phase liquid-immersed transformers with power ≤ 3150 kVA and winding voltages U_{m1} ≤ 24 kV and U_{m2} ≤ 3.6 kV, which is the transformer category we focus on in this whitepaper. The table prescribes maximum values for the load losses P_k and for the no-load losses P_0.

The original requirements came into force on 1 July 2015 (Tier 1 of the regulation). After a revision, more stringent values for P_k and P_0 were set, which came into force on 1 July 2021 (Tier 2).

An exception was included in the latest edition of the medium-power transformer regulation. Where a one-to-one replacement by a Tier 2 compliant unit entails disproportionally high installation costs, the replacement transformer is required to meet Tier 1 efficiency values only. Installation costs, including the cost of substation housing and additional floor space, are regarded as disproportionate if they are higher than the net present value of the avoided electricity losses of a Tier 2 compliant unit over its expected service life. Put simply, if the life-cycle cost of a Tier 2 compliant unit is higher than that of a Tier 1 compliant unit, you are allowed to opt for the latter.

	Tier 1 (from 1 July 2015)		Tier 2 (from 1 July 2021)	
Rated Power (kVA)	Maximum load losses P_k (W) (*)	Maximum no-load losses P_o (W) (*)	Maximum load losses P_k (W) (*)	Maximum no-load losses P_o (W) (*)
≤ 25	C_k (900)	A_o (70)	A_k (600)	A_o − 10 % (63)
50	C_k (1 100)	A_o (90)	A_k (750)	A_o − 10 % (81)
100	C_k (1 750)	A_o (145)	A_k (1 250)	A_o − 10 % (130)
160	C_k (2 350)	A_o (210)	A_k (1 750)	A_o − 10 % (189)
250	C_k (3 250)	A_o (300)	A_k (2 350)	A_o − 10 % (270)
315	C_k (3 900)	A_o (360)	A_k (2 800)	A_o − 10 % (324)
400	C_k (4 600)	A_o (430)	A_k (3 250)	A_o − 10 % (387)
500	C_k (5 500)	A_o (510)	A_k (3 900)	A_o − 10 % (459)
630	C_k (6 500)	A_o (600)	A_k (4 600)	A_o − 10 % (540)

Article 7 of the latest edition of the Transformer Ecodesign Regulation prescribes a future review of the regulation to reflect technical progress. A draft revision proposal must be ready by 1 July 2023. The article lists a number of issues this revision must particularly address, including “the possibility and appropriateness of covering environmental impacts other than energy in the use phase, such as noise and material efficiency”.

THE EU GREEN DEAL

In the Green Deal, published in December 2019, the European Commission sets the objective of reducing net greenhouse gas emissions in the EU to zero by 2050 to become the first climate neutral continent. The declaration specified that this bold ambition should not come at the cost of other major objectives. It aims to decouple economic growth from resource use and insists that no person and no place may be left behind. The Green Deal has recently been associated with the Covid-19 Economic Recovery Plan. One third of the €1.8 billion recovery plan budget will go to investment supporting the Green Deal.

FIT FOR 55% BY 2030

Following a detailed investigation, the European Commission concluded that the current policy framework and carbon emission objective for 2030 were insufficient for attaining the 2050 goal expressed in the Green Deal, since it would place an disproportionately high burden on the period after 2030. The Commission therefore decided to revise the 2030 objective and elect for a 55% net carbon emission reduction by that year compared to 1990. A detailed impact assessment of this new objective was carried out, which led to the *Fit for 55%* legislative package, published on 14 July 2021 [3].

Two conclusions from the *Fit for 55%* impact assessment are relevant to this whitepaper:

- Energy performance policies should be intensified, which requires a revision of the EED, EPBD and Ecodesign legislation [4, p.32-35]. The greatest potential for additional policy initiatives was identified in the Buildings, Industry and ICT sectors. Electricity networks are not mentioned explicitly, but it seems self-evident that, in this context, the existing Tier 2 Ecodesign regulation on distribution transformers should be rolled out rigorously.

- The additional decarbonization efforts will translate into a reinforced trend towards electrification, mainly through heat pumps and electric vehicles. The impact assessment formulates it as follows: "*Policies targeting the electrification of end-use sectors (for example fostering the deployment of heat pumps and electric vehicles) helps reduce final energy consumption and creates an additional pull for electricity supply that is increasingly renewables-based. Electrification is also more efficient compared to the use of biomass-based fuels and the primary energy needed to produce hydrogen or e-fuels*." [4, p.40].

In total, electricity consumption is expected to increase 10% by 2030 and 40% by 2050 — increases which can be attributed to electrification, mitigated by energy performance optimization. The expected increase is unevenly spread over sectors and over time:

Energy (TWh)	Year	Services	Industry	Residential	Transport	Total
	2015	728	879	733	49	2442
	2030	755	917	863	162	2698
	2050	823	1166	892	549	3431
Delta vs. 2015	**Year**	**Services**	**Industry**	**Residential**	**Transport**	**Total**
	2030	-3%	4%	18%	231%	10%
	2050	5%	33%	22%	1024%	40%

The services sector will initially see a decrease in energy consumption due to energy efficiency efforts and the fact that the opportunities for electrification are somewhat limited. In industry, a radical shift towards electricity (e.g. electric melting furnaces) is expected between 2030 and 2050. The residential sector will see a steady rise in electricity consumption until 2050, mainly due to heat pump installations linked to the renovation rate of dwellings. The sharpest increase is in the road transport sector, which is a new domain for electricity. The rise in electricity consumption in the road transport sector, already steep leading up to 2030, will be even steeper between 2030 and 2050.

Circular Economy Action Plan

The EU Green Deal emphasized that its decarbonization ambition should be accomplished with maximum resource efficiency. This objective took practical form in a new Circular Economy Action Plan published in March 2020. The plan presents a set of initiatives that will lead to a coherent policy framework for product circularity. The core of this legislative initiative is set to widen the Ecodesign Directive beyond energy performance as the only criterium and beyond energy-related products as the sole target.

The recent revision of the Methodology for Ecodesign of Energy-related Products (MEErP) expresses the Circular Economy Action Plan in more concrete terms. It provides reporting tools to record the use of materials and other resources such as energy and water, as well as emissions into the air and water over the entire life cycle of a product. More particularly, it looks at aspects such as critical material use, recyclability, reparability, and upgradability. The aim is that engineers take all these factors into account at product design phase.

CONCEPT OF THE SUSTAINABLE PEAK LOAD TRANSFORMER

At the origin of the sustainable peak load concept are the following four observations:

1. The rated power of a transformer is expressed universally in IEEE and IEC standards as the amount of power that can be delivered without exceeding a maximum temperature rise of 65°C in the windings. This temperature rise limit aims to achieve a certain level of reliability and lifespan of the unit.

2. Over the past 30 years, there has been a growing interest in reducing the energy losses of transformers, which has resulted in mandatory minimum energy performance standards in many countries and regions of the world. The efforts to meet stringent load loss restrictions without exceeding the space restrictions of distribution transformer cabinets has led to several technological evolutions. One type of innovation was directly aimed at reducing the energy losses without increasing the size of the transformer. The main examples are the use of highly conductive material for the windings, and of magnetic steel with reduced hysteresis and eddy current losses. Another type of innovation was the introduction of electrical insulation materials that allowed the design to be more compact without compromising the insulation level. Thermally upgraded paper as a solid insulation and the use of natural esters as liquid insulation are the main examples – the latter also having other major advantages which are not relevant here. A distribution transformer using these technologies could increase its rated power, in theory, since it can withstand a temperature rise of 95°C without compromising on reliability and expected lifetime. Such increases were not instigated to meet the stringent load loss restrictions, originally the main driver for the innovation. As a result of all these evolutions, most distribution transformers today are labelled for their compliance with energy performance regulations and may never come close to their maximum temperature.

3. Until recently, public distribution network loadings have been estimations only, not measured. With the introduction of smart meters, extensive measurement campaigns have now recorded full-year kWh data at 15-, 30- or 60-minute intervals. According to these new data, distribution transformer loadings tend to be lower than initially thought, with average load factors around 15%, root mean square (RMS) equivalent average around 30%, and peak loads close to 80% of nameplate capacity [5 and 2, p. 151].

4. At low load levels, the relative importance of the load losses diminishes, and the relative importance of the no-load losses increases. As a result, choosing a smaller transformer for the same job will often have little influence on the total annual energy losses of the unit. The increase in load losses during peak hours will be balanced or exceeded by the 24/7 decrease in no-load losses.

The latter observation leads directly to the concept of the sustainable peak load transformer. The idea is to choose a smaller transformer B for the same job as a conventionally selected transformer A.

- The "sustainable peak capacity" of transformer B is set at the same power as that of transformer A. This is permitted due to the fact that the transformer can withstand the resulting maximum temperature rise in the windings without compromising reliability or cutting short the transformer's expected lifetime. Technically, the transformer could be loaded continuously at this kVA rating but doing so would result in high total energy losses.

- The "rated nameplate capacity" of transformer B is the value which limits the temperature rise in the conventional way and is consequently lower than the sustainable peak capacity. The transformer will meet the energy performance regulations for this nameplate capacity.

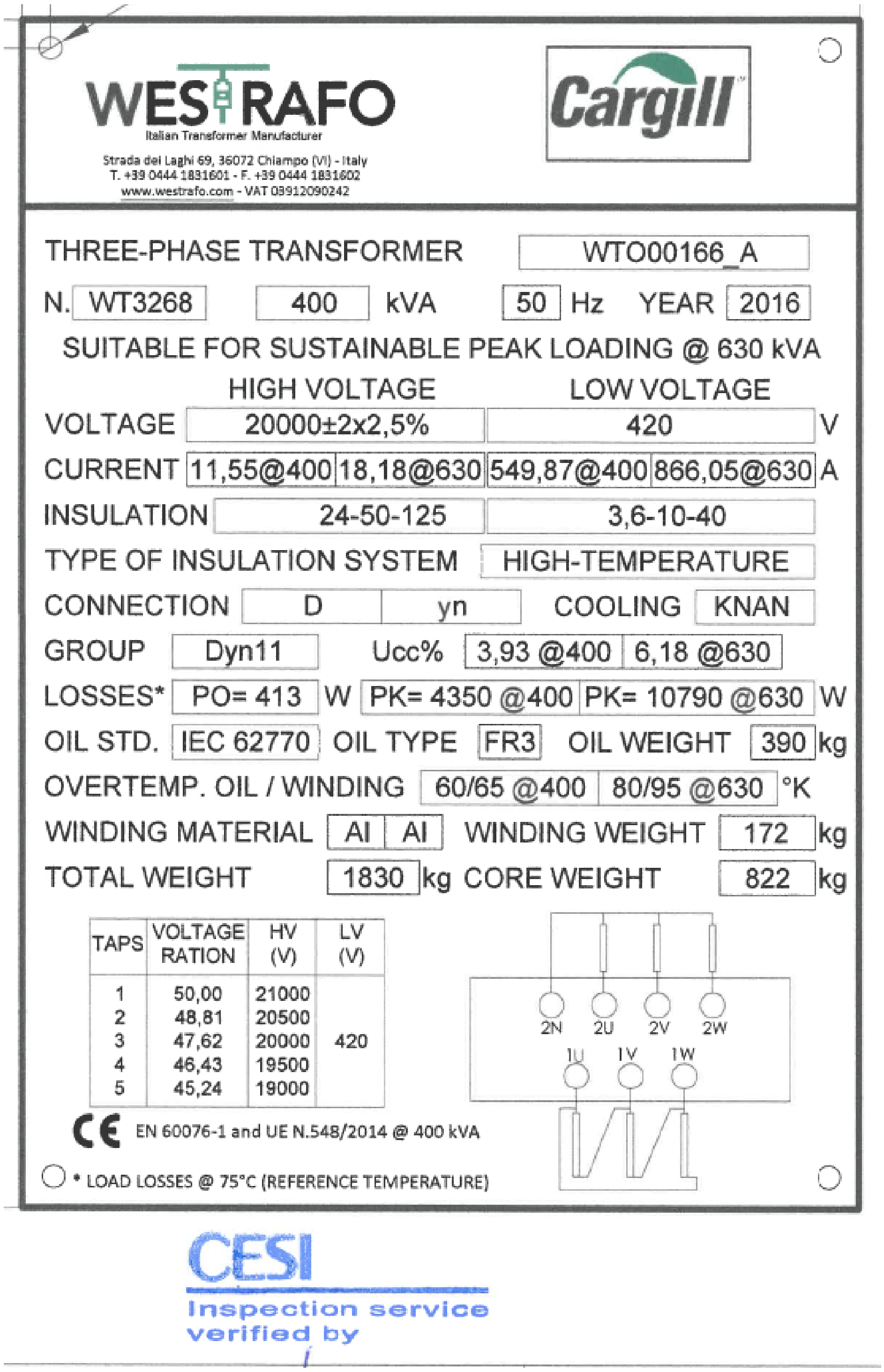


FIGURE 1 – NAMEPLATE OF A 400 KVA / 630 KVA WESTRAFO SUSTAINABLE PEAK LOAD TRANSFORMER TAKEN INTO SERVICE IN 2016. LOAD LOSSES AT 400 KVA COMPLY WITH TIER 1 ECODESIGN REQUIREMENTS (4,350 W < 4,600 W). AT 630 KVA, THEY ARE ABOVE THE TIER 1 MINIMUM VALUE (10,790 W > 6,500 W). NO LOAD LOSSES COMPLY WITH THE TIER 1 MIINMUM FOR A 400 KVA TRANSFORMER (413 W < 430 W) AND ARE SIGNIFICANTLY BELOW THE TIER 1 MINIMUM FOR A 630 KVA UNIT (413 W << 600 W).

MODELLING THE POTENTIAL BENEFITS

A group of experts, under the direction of the European Copper Institute, conducted a modelling exercise to assess the potential impact of selecting sustainable peak load units on material use, total losses, and transformer cost, for all transformer replacements in public distribution networks of the EU.

The model took the commonly used 400 kVA – 24 kV/0.4 kV transformer as a starting point, as in the 2013 Ecodesign impact assessment [**¡Error! Marcador no definido.**]. The model then calculated the difference between replacing all end-of-life 400 kVA units in the EU with conventional 540 kVA units, or with a sustainable peak load 400 kVA/540 kVA unit. See Annex I for a detailed description of the model and its assumptions.

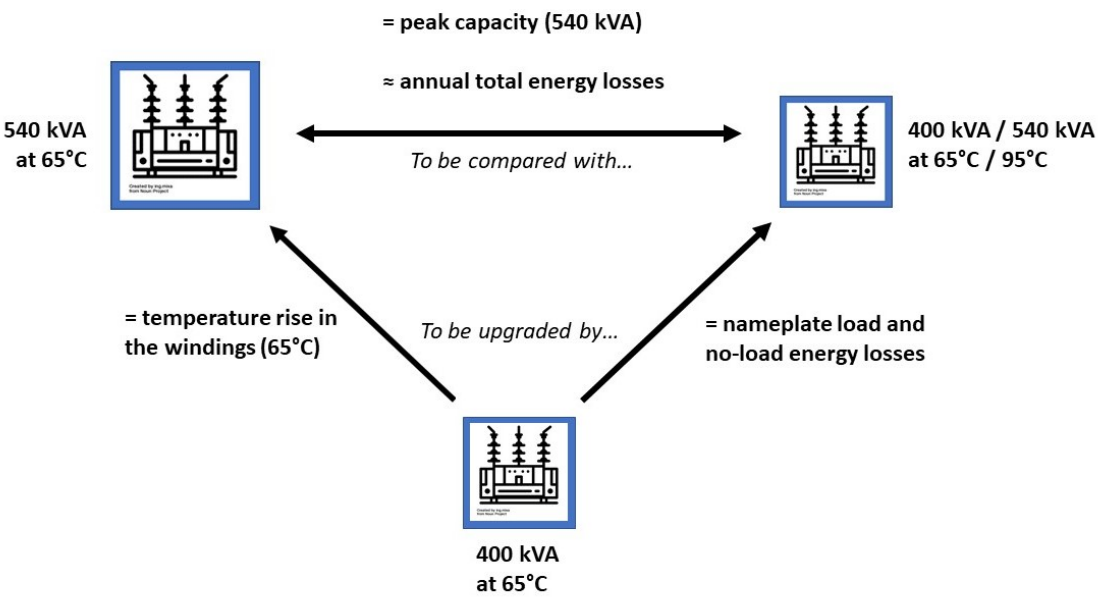


FIGURE 2 – THE SUSTAINABLE PEAK LOAD TRANSFORMER CONCEPT (SUBSTATION TRANSFORMER BY ING.MIXA FROM THE NOUN PROJECT)

The modelling exercise involved transformer variants as follows:

- With M0H, M3, or amorphous magnetic steel in the core;
- With aluminium / aluminium (Al/Al) or with aluminium / copper (Al/Cu) as a conductor material in the low voltage / high voltage windings.

The following comparisons are discussed here:

- a M0H Al/Al conventional unit of 540 kVA with a M0H Al/Al sustainable peak load unit of 400 kVA/540 kVA;
- a M0H Al/Al conventional unit of 540 kVA with a M0H Al/Cu sustainable peak load unit of 400 kVA/540 kVA.

An additional comparison can be found in Annex II.

SIMILAR ENERGY PERFORMANCE

Concerning the energy performance, a distinction should be made between the nameplate power losses of the transformer, expressed in Watts, and its annual energy losses, expressed in kWh. The former is subject to regulation, while the latter must be taken into account when evaluating the unit's environmental performance.

The 400 kVA / 540 kVA sustainable peak load transformer is designed according to the prevailing minimum energy performance standards (MEPS) of a 400 kVA unit (see Table 3), i.e. 3250 W load losses and 387 W no-load losses (see Table 3, Tier 2 MEPS). The load losses of the sustainable peak load unit will exceed this nameplate value during the short periods of peak load (400 kVA < loading < 540 kVA). However, the no-load losses of the sustainable peak load unit are fixed at 387 W, while a conventional 540 kVA unit will have 484 W of no-load losses. For load profiles with short peaks and a low average loading — as is the case in distribution networks — the increase in total annual load losses will be more or less compensated by the decrease in annual no-load losses, as demonstrated by the modelling exercise results.

Technology	Conventional Al/Al 540 kVA	Dual nameplate Al/Al 400 kVA / 538 kVA	Conventional Al/Al 540 kVA	Dual nameplate Al/Cu 400 kVA / 532 kVA
Rating at + 65°C rise (kVA)	540	400	540	400
Rating at + 95°C rise (kVA)		538		532
LV windings / HV windings	Al / Al	Al / Al	Al / Al	Al / Cu
Type of liquid insulation	Mineral oil	FR3	Mineral oil	FR3
Steel type	M0H	M0H	M0H	M0H
Energy losses (TWh)				
Annual average 2020 - 2050	20.9	20.8 (-0.3%)	20.9	20.9 (=)
Cumulative 2020 - 2050	647.7	645.9 (-0.3%)	647.7	647.5 (=)

TABLE 3 – COMPARING ANNUAL AND CUMULATIVE ENERGY LOSSES (MODELLING EXERCISE)

Based on the above assumptions, the total annual and cumulative energy losses of the sustainable peak load units were calculated to be very similar to those of a conventional unit.

The CO_{2eq} emissions associated with these losses depend on the energy mix for electricity generation. The CO_{2eq} intensity of the energy mix is decreasing steadily and is targeted to become zero by 2050.

Substantial material savings

The sustainable peak load concept can substantially increase the material efficiency of a distribution transformer. The following table compares the cumulative material use of a conventional unit with two types of sustainable peak load units over the period 2020 to 2050, from data obtained by the modelling exercise.

Technology	Conventional Al/Al 540 kVA	Dual nameplate Al/Al 400 kVA / 538 kVA	Conventional Al/Al 540 kVA	Dual nameplate Al/Cu 400 kVA / 532 kVA
Rating at + 65°C rise (kVA)	540	400	540	400
Rating at + 95°C rise (kVA)		538		532
LV windings / HV windings	Al / Al	Al / Al	Al / Al	Al / Cu
Type of liquid insulation	Mineral oil	FR3	Mineral oil	FR3
Steel type	M0H	M0H	M0H	M0H
Material use (cumulative 2020-2050)				
Steel (kton)	2877	2495 (-13%)	2877	2157 (-25%)
Aluminium (kton)	1158	960 (-17%)	1158	393
Copper (kton)	0	0	0	1022
Liquid (1000 m^3)	1422	1301	1422	1147
Total weight (kton)	**7304**	**6513 (-11%)**	**7304**	**6452 (-12%)**

TABLE 4 – COMPARING THE CUMULATIVE MATERIAL USE (MODELLING EXERCISE)

The sustainable peak load units use less steel, winding material and liquid insulation. The total weight of the units is also substantially less than the conventional units.

With less material being used, the CO_{2eq} emissions associated with producing it will be avoided. The carbon intensity of material production is expected to decline less steeply compared to the carbon intensity of electricity generation over the next 10 to 20 years. As a result, we will see an increase in the relative importance of carbon emissions associated with material use compared to those associated with electricity generation.

The improved material efficiency of sustainable peak load transformers can be an important trump card in the context of the growing emphasis on material use and recyclability in EU regulation.

ECONOMIC ANALYSIS

The modelling exercise demonstrated that the material cost and purchase price of a sustainable peak load transformer are comparable to those of an equivalent conventional transformer (where both use aluminium for the low voltage and high voltage windings).

The lifetime maintenance costs are expected to be similar too, since sustainable peak load unit reliability is no different from that of a conventional unit. The lifecycle cost of the energy losses will also be comparable for both units, as demonstrated in the *Similar energy performance* chapter.

Technology	Conventional Al/Al 540 kVA	Dual nameplate Al/Al 400 kVA / 538 kVA	Conventional Al/Al 540 kVA	Dual nameplate Al/Cu 400 kVA / 532 kVA
Rating at + 65°C rise (kVA)	540	400	540	400
Rating at + 95°C rise (kVA)		538		532
LV windings / HV windings	Al / Al	Al / Al	Al / Al	Al / Cu
Type of liquid insulation	Mineral oil	FR3	Mineral oil	FR3
Steel type	M0H	M0H	M0H	M0H
Cost (cumulative 2020-2050)				
Total material cost (M€)	10509	10715 (+2%)	10509	13848 (+32%)
Selling price (M€)	21894	22323 (+2%)	21894	28850 (+32%)

TABLE 5 – COMPARING THE CUMULATIVE MATERIAL COST AND PURCHASE PRICE (MODELLING EXERCISE)

The table shows that a sustainable peak load unit using copper for the high voltage winding costs 32% more than a conventional transformer using aluminium for the high voltage winding. The price premium is largely due to the extra cost of using copper, but most of this copper can be recycled with very high purity (1A grade copper scrap is 99.99% pure) and re-used as high-conductivity copper. Aluminium, however, is recycled at lower grade to be used in second life products which have less demanding purity requirements. This is due to the fact that electrical aluminium comes in many different alloys, requiring laboratory analysis if the material is to be recycled for the same application, which is not economically feasible. Because of the high degree of recyclability of copper windings, their end-of-life value is six to seven times higher than that of aluminium windings. This means that the price premium can largely be recovered through the scrap value at end-of-life.

A major economic advantage of the sustainable peak load transformer is its compactness. Due to the transition away from fossil fuels, and the resulting electrification of energy end use, substantial growth in electricity consumption is expected in some sectors supplied by distribution networks. The sustainable peak load transformer provides the opportunity to upgrade transformer peak power while keeping the same unit dimensions, saving in installation of distribution grid upgrades. This will mean that such upgrades can be made at an earlier stage, making the distribution grid more robust.

PROVEN TECHNOLOGY WITH MULTIPLE BENEFITS

The extent to which a transformer can withstand certain temperatures, without compromising reliability or lifetime, is defined by its insulation's *thermal class*. The higher its thermal class, the more the transformer can withstand an overload capacity that goes beyond its conventional power rating at 65°C. The highest thermal class can be achieved by using a combination of natural esters as a transformer liquid [6] and thermally upgraded paper as a solid insulation [7][8]. These are both advanced but proven materials with multiple benefits.

Natural ester transformer liquid

Natural esters were initially developed to be a less flammable transformer liquid than mineral oil and more environmentally friendly than both mineral and PCB (askarel) oils. The fire resistance of natural esters stems from their high fire point. In relation to the environment, they are highly biodegradable, proven to be non-toxic, and have a low infiltration rate in soil, which is crucial when there are oil spills from the transformer. As a result of these qualities, the containment structure of a transformer using natural esters can be simpler and smaller than if the unit uses mineral oil. This makes the entire installation more compact and cost-effective.

Natural esters derive from renewable sources and are classified as carbon neutral, resulting in lower CO_{2eq} emissions associated with the transformer unit's production. On the downside, they are more expensive than mineral oil. They also have lower oxidation stability, which means they cannot be used in free-breathing units.

The higher thermal class that can be achieved through using natural esters results in an overload capacity without compromising transformer reliability or lifetime, which is the most significant characteristic for the concept presented in this whitepaper.

Natural esters have been used successfully in more than 2.5 million transformers over a period of 20 years, and are accompanied by a complete framework of standards and guidance for condition assessment.

Thermally upgraded paper

Various types of thermally upgraded paper have been developed over the years, with various levels of insulation quality. They are a proven technology which has been used in electrical equipment for more than 50 years, and in transformers for more than 30 years. Examples include Kraft paper, Nomex® paper and INSULutions® DPE.

The initial purpose of using thermally upgraded paper was to increase unit loading capacity without increasing its weight. These characteristics were highly valued for traction transformers and for pole-mounted transformers used in the US.

Thermally upgraded paper increases the thermal class of the insulation, resulting in higher loading capacity. By combining the latest paper technology with natural esters as a transformer fluid, a thermal class of 140 can be achieved, which is well-suited for sustainable peak load transformers.

CONCLUSION

The following important observations emerged from the modelling exercise to assess the impact of selecting sustainable peak load units for all transformer replacements in public distribution networks in the EU:

- The total annual energy losses of a sustainable peak load unit are comparable with or better than those of a conventional unit.

- The material savings potential of sustainable peak load transformers is substantial, with reductions in total weight of 11 - 15%.

- The purchase price of a sustainable peak load transformer is comparable to that of a conventional transformer, if all the other parameters remain the same.

In light of these conclusions, widespread application of the sustainable peak load concept in the EU public distribution networks is recommended. It would maximize both the energy efficiency and material efficiency of public distribution transformers.

ANNEX I: ASSUMPTIONS AND METHODS USED IN THE MODELLING EXERCISE

The model took the 400 kVA – 24 kV/0.4 kV transformer as a starting point, and then calculated the difference between replacing all end-of-life 400 kVA units in the EU with conventional 540 kVA units, or with sustainable peak load 400 kVA/540 kVA units.

ASSUMPTIONS

STOCK AND SALES

The 2013 Ecodesign Impact Assessment [1] estimated that there were 2.25 million distribution transformers (400 kVA equivalent) in use by distribution system operators (DSOs) in the EU in 2005. The model assumed an annual stock growth of 1.4% and an annual replacement rate of 2.5%, resulting in an annual sales figure of 3.9% of the installed stock. The annual replacement rate of 2.5% means that the transformer lifetime was assumed to be 40 years (100 * 1/40 = 2.5).

Using these figures, we calculated the stock of public distribution transformers (400 kVA equivalent) to be 2,786,879 units in 2020.

PRESENT AND FUTURE LOAD FACTORS

Three different load factor definitions can be found in the literature:

- *Load factor* $\alpha = P_{avg} / S$, with P_{avg} the average load, and S the nameplate load
- *RMS load factor* P_{RMS} = load factor x load form factor = $(P_{avg} / S) \times (P_{RMS} / P_{avg})$
- *Utility load factor* = P_{avg} / P_{max} with P_{max} the maximum load that has been delivered by the transformer (with $P_{max} < S$)

Here we will use the normal load factor α unless otherwise stated.

The average distribution network load factor in 2020 was estimated to be 16.6%, a figure calculated from the following:

- The installed transformer capacity of 1,115 MVA in 2020, as predicted by the 2013 Ecodesign Impact Assessment [1];
- The end use electricity supplied through distribution grids in 2020, estimated to be 1,624 TWh. This was calculated from the electricity use figures of 780 TWh (services sector), 890 TWh (industrial sector), 750 TWh (residential sector) and 60 TWh (transport sector) as discussed in the Green Deal impact assessment [4]. The share of the electricity supplied through the distribution grid in each sector was estimated at 85%, 17%, 100% and 100% respectively.
- An estimation was made of how load factors will evolve by 2050, differentiated by sector:
- Residential sector 2050 load factor = 18% — based on a substantial load increase due to the installation of heat pumps and EV charging points, slightly mitigated by the potential storage capacity for peak shaving of both applications;
- Services sector 2050 load factor = 16.6% — based on a load increase entirely compensated by energy efficiency efforts;
- Road transport sector 2050 load factor = 25% — based on documented predictions of load factors in public EV charging stations, with limited use of EV batteries for storage;
- Industrial sector 2050 load factor = 18% — based on a substantial load increase, mitigated by numerous peak shaving opportunities;
- Average 2050 load factor = 18.6%.

FUTURE INSTALLED CAPACITY OF EXISTING AND NEW UNITS

The future total installed capacity was predicted based on:

- The growth in electricity consumption supplied by distribution networks in different sectors (residential, services, road transport, industry), as estimated in the EU Green Deal impact assessment [4] (see Annex II for details);

- An estimation of how the share of electricity supplied through the distribution grid in each of these sectors will evolve. See the following table:

Share of electricity supplied through DSOs				
Year / Sector	Services	Industry	Residential	Transport
2015	85%	15%	100%	100%
2020	85%	17%	100%	100%
2030	85%	18%	100%	100%
2040	85%	18%	100%	95%
2050	85%	18%	100%	90%

TABLE 6 – SHARE OF ELECTRICITY SUPPLIED THROUGH DISTRIBUTION SYSTEM OPERATORS

  - The figure for the industrial sector is expected to increase slightly due to the electrification of heating and cooling systems in SMEs;
  - The figure for the transport sector is expected to decrease after 2030 due to the development of fast charging stations connected directly to the transmission grid.

The installed capacity of existing units (400 kVA) has been reduced by 2.5% for each year, which is the replacement rate as indicated in the 2013 Ecodesign impact assessment [1].

The installed capacity of new units (540 kVA) in each year was calculated from the difference between the predicted total installed capacity and the remaining capacity of existing units.

The total number of new 540 kVA units was calculated from the installed capacity of new units and the gradual evolution of load factors in each sector from 16.6% in 2020 to the estimated load factors per sector given above for 2050.

BILLS OF MATERIAL

The model is based on the following bills of material for the five transformer types discussed in this whitepaper:

Bill of material	Conventional (base case)	Conventional	Conventional	Dual nameplate	Dual nameplate
Rating at 65ºC rise (kVA)	400	540	540	400	400
Rating at 95ºC rise (kVA)				538	532
Effective rating (kVA)	400	540	540	538	532
LV/HV winding	Al/Al	Al/Al	Al/Cu	Al/Al	Al/Cu
Liquid type	Mineral oil	Mineral oil	Mineral oil	FR3	FR3
Steel type	M0H	M0H	M0H	M0H	M0H
Steel (kg)	1056	1379	1267	1191	1018
Aluminium (kg)	292	555	239	458	186
Copper (kg)	0	0	599	0	482
Liquid (litres)	511	681	647	621	541
Total weight (kg)	**2639**	**3500**	**3629**	**3109**	**3045**

TABLE 7 – BILL OF MATERIAL FOR EACH OF THE FIVE TRANSFORMER TYPES DISCUSSED IN THIS WHITEPAPER

PRICES

The model used 2017 prices for copper, aluminium, M0H steel, mineral oil, and natural ester FR3, as follows:

Prices (2017)	
Copper (€/kg)	5.49
Aluminium (€/kg)	2.47
Steel M0H (€/kg)	2.04
Mineral oil (€/kg)	1.39
FR3 (€/l)	2.78

TABLE 8 – MATERIAL PRICES

The material cost was assumed to 48% of the total purchase price of the transformers.

ENERGY LOSSES

A distinction should be made between the nameplate power losses of the transformer, expressed in Watts, and its annual energy losses, expressed in kWh.

The nameplate power losses are restricted by the Ecodesign regulation. The maximum load losses and no-load losses for three-phase liquid-immersed medium power transformers according to Tier 1 (from 1 July 2015) and Tier 2 (from 1 July 2021) of the relevant Ecodesign regulation are given in *Table 1.*

For the annual energy loss calculation see below.

LOAD DISTRIBUTION

An estimation of the load distribution is required in order to calculate the annual energy losses. The load distributions were set out based on the following assumptions:

- An average RMS utility load factor (P_{RMS} / P_{max}) of 28% from an analysis carried out in the US with the utility companies Dominion Energy, Duke Energy and Toronto Hydro [9];
- An average peak load P_{max} at 80% of the nameplate load S;
- The load factors (P_{avg} / S) per sector as described above (for 2020, and their gradual evolution to 2050).

MATERIAL USE CALCULATION

The total annual material use in each case was calculated from the relevant transformer's BOM and the number of units sold that year.

COST CALCULATION

The total annual cost in each case was calculated from the relevant transformer's BOM, the number of units sold that year, and the material prices.

ANNUAL ENERGY LOSS CALCULATION

The total annual energy losses in each case were calculated from the number of units in use, their nameplate energy losses, the load factor, and the load distribution.

ANNEX II: FURTHER RESULTS FROM THE MODELLING EXERCISE

In the “Modelling the potential benefits” chapter, we presented comparisons in terms of annual energy consumption, material use, and purchase price between a conventional transformer using aluminium as a conductor material in the high voltage windings — the most common type for public distribution transformers — and a sustainable peak load transformer using either aluminium or copper for the high voltage windings. Here we present a comparison for the case where copper is used for the high voltage windings in both the conventional transformer and the sustainable peak load transformer.

More specifically, the following tables compare a M0H, Al/Cu, 540 kVA conventional unit with a M0H, Al/Cu, 400 kVA/540 kVA sustainable peak load unit in terms of annual energy consumption, material use, and purchase price.

Technology	Conventional Al/Cu 540 kVA	Dual nameplate Al/Cu 400 kVA / 532 kVA
Rating at + 65°C rise (kVA)	540	400
Rating at + 95°C rise (kVA)		532
LV windings / HV windings	Al / Cu	Al / Cu
Type of liquid insulation	Mineral oil	FR3
Steel type	M0H	M0H
Energy losses (TWh)		
Annual average 2020 - 2050	20.9	20.9 (=)
Cumulative 2020 - 2050	647.3	647.5 (=)

TABLE 9 – COMPARING ANNUAL AND CUMULATIVE ENERGY LOSSES (MODELLING EXERCISE)

Technology	Conventional Al/Cu 540 kVA	Dual nameplate Al/Cu 400 kVA / 532 kVA
Rating at + 65°C rise (kVA)	540	400
Rating at + 95°C rise (kVA)		532
LV windings / HV windings	Al / Cu	Al / Cu
Type of liquid insulation	Mineral oil	FR3
Steel type	M0H	M0H
Material use (cumulative 2020-2050)		
Steel (kton)	2645	2157 (-18%)
Aluminium (kton)	500	393 (-21%)
Copper (kton/year)	1251	1022 (-18%)
Liquid (1000 m^3)	1351	1147
Total weight (kton)	**7574**	**6452 (-15%)**

TABLE 10 – COMPARING THE CUMULATIVE MATERIAL USE (MODELLING EXERCISE)

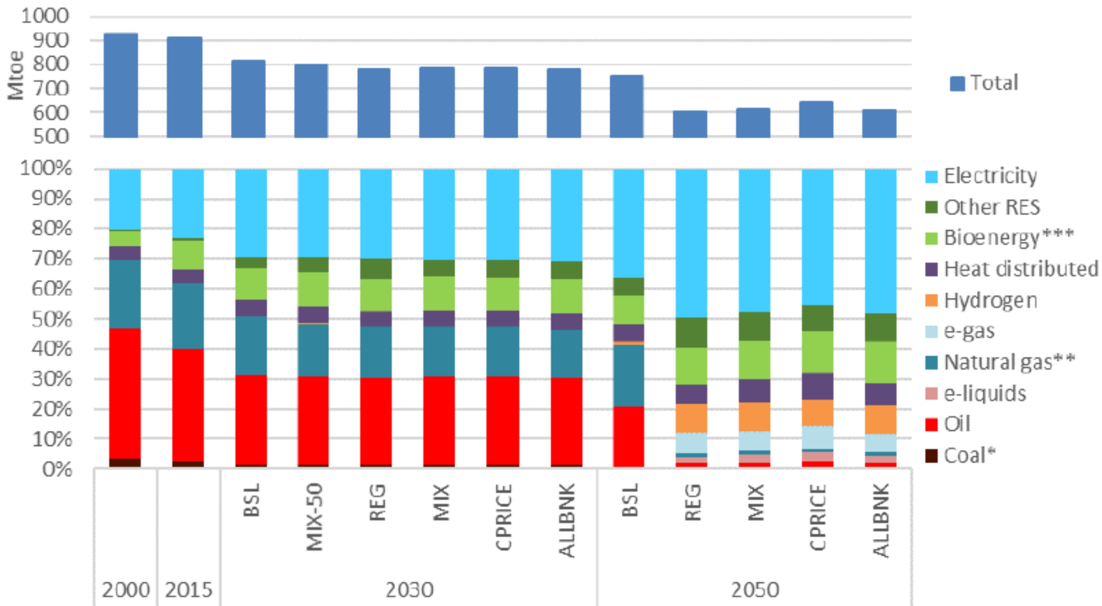
Technology	Conventional Al/Cu 540 kVA	Dual nameplate Al/Cu 400 kVA / 532 kVA
Rating at + 65°C rise (kVA)	540	400
Rating at + 95°C rise (kVA)		532
LV windings / HV windings	Al / Cu	Al / Cu
Type of liquid insulation	Mineral oil	FR3
Steel type	M0H	M0H
Cost (cumulative 2020-2050)		
Total material cost (M€)	15190	13848 (-9%)
Selling price (M€)	31645	28850 (-9%)

TABLE 11 – COMPARING THE MATERIAL COST AND PURCHASE PRICE (MODELLING EXERCISE)

We see that savings are made in both material use and purchase price. The annual energy use stays essentially the same.

ANNEX III: ELECTRIFICATION TRENDS

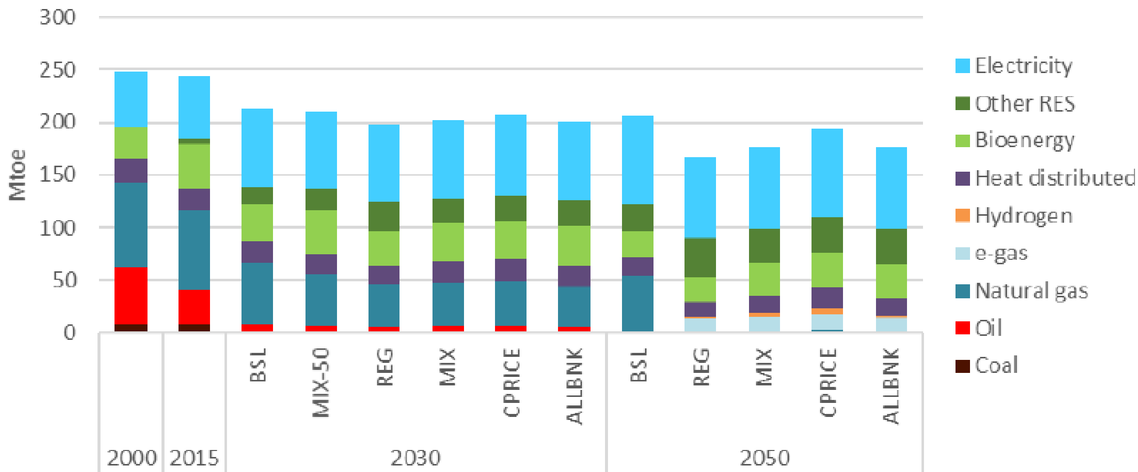
The impact assessment in the EU Green Deal ("Stepping up Europe's 2030 climate ambition") estimated the rising share of electricity in energy end use by 2030 and 2050 [**¡Error! Marcador no definido.**]. It also provides detailed estimations for the different sectors supplied by distribution networks (residential, services, road transport, industry).



*Note: * includes peat, oil shale, ** includes manufactured gases, *** solid biomass, liquid biofuels, biogas, waste*

FIGURE 3 – FINAL ENERGY DEMAND BY ENERGY CARRIER (EU); ESTIMATES FOR 2030 AND 2050 DEPENDING ON THE DECARBONISATION POLICY SCENARIO [¡ERROR! MARCADOR NO DEFINIDO., **FIGURE 37]**

The share of electricity in final demand is expected to go up from 23% in 2015 to 29 - 31% in 2030 and to 46-50% in 2050, depending on the decarbonization policy scenario. This increase is driven by the uptake of heat pumps in buildings, as well as the electrification of industrial processes and transport.



Source: 2000-2015: Eurostat, 2030-2050: PRIMES model

FIGURE 4 – ENERGY DEMAND IN RESIDENTIAL BUILDINGS BY ENERGY CARRIER (EU); ESTIMATES FOR 2030 AND 2050 DEPENDING ON THE DECARBONISATION POLICY SCENARIO [¡ERROR! MARCADOR NO DEFINIDO., **FIGURE 55]**

In residential buildings, electricity use is expected to increase from ~50 Mtoe in 2015 to 75 Mtoe in 2030, and to remain at this level between 2030 and 2050. This is based on an expected substantial load increase due to the installation of heat pumps and EV charging points, slightly mitigated by the expected future storage capacity enabling peak shaving in both applications.

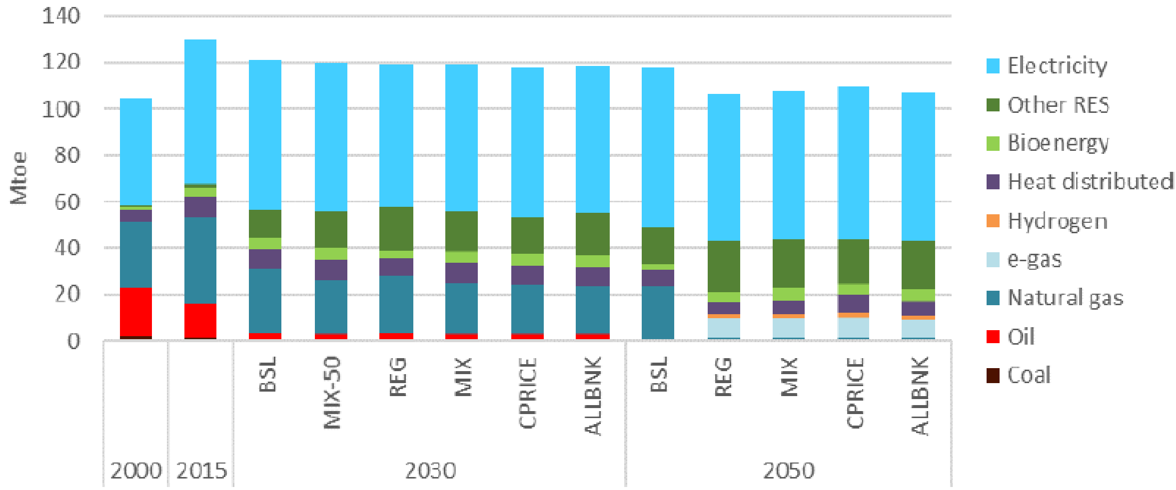
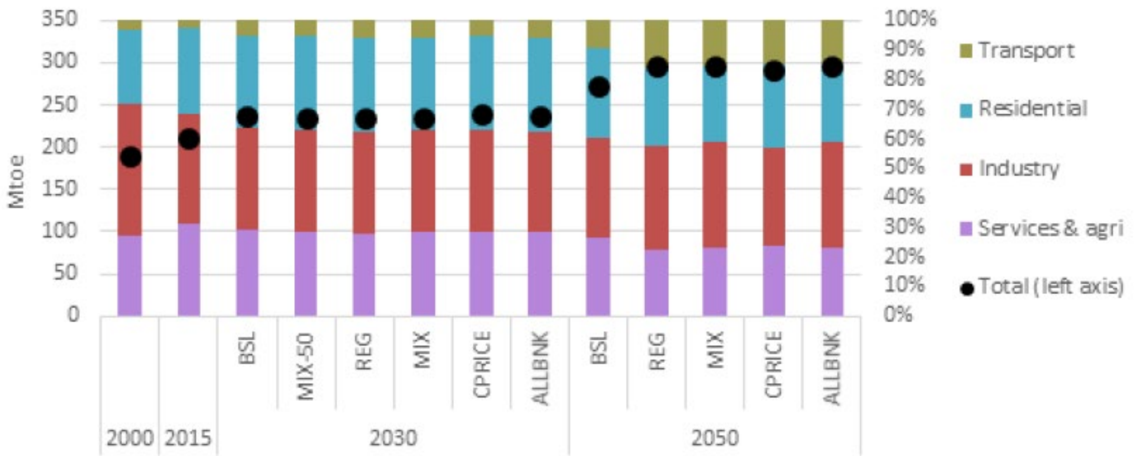


FIGURE 5 – ENERGY DEMAND IN THE SERVICES SECTOR, BY ENERGY CARRIER (EU); ESTIMATES FOR 2030 AND 2050 DEPENDING ON THE DECARBONISATION POLICY SCENARIO [¡ERROR! MARCADOR NO DEFINIDO.**, FIGURE 56]**

In the services sector, electricity use is expected to remain more or less constant at the 2015 figure of ~60 Mtoe. This is based on the assumption that the load increase will be entirely compensated by energy efficiency efforts.



Source: 2015: Eurostat, 2030-2050: PRIMES model

FIGURE 6 – FINAL ELECTRICITY DEMAND BY SECTOR (EU); ESTIMATES FOR 2030 AND 2050 DEPENDING ON THE DECARBONISATION POLICY SCENARIO [¡ERROR! MARCADOR NO DEFINIDO.**, FIGURE 44]**

The share of road transport (EV charging stations) in the total electricity demand is expected to rise to 3 - 5% by 2030 and to 10 - 15% by 2050, depending on the decarbonization policy scenario.

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