The Environmental Impact of Every MWh of Electricity Losses Over the Next 20 Years in the EU

Bruno De Wachter and Fernando Nuño

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Bruno De Wachter[1] and Fernando Nuño[2]

[1] Consultant for the International Copper Association Europe, Avenue de Tervueren 168, 1150 Woluwe Saint-Pierre
[1] International Copper Association Europe, Avenue de Tervueren 168, 1150 Woluwe Saint-Pierre

Abstract. The European power generation system is well on its way to decarbonization, but that does not take away from the need for continuing efforts to improve energy efficiency. Power generation will continue to emit greenhouse gases for some years to come, and building renewable generation capacity has an environmental impact in itself. To illustrate this, we calculated what impact every MWh/y of electricity losses would have in the EU in the period 2025 to 2045, and quantified this impact in terms of greenhouse gas emissions, land use, and material use. We also calculated the quantity of additional material needed in a typical induction motor to improve energy efficiency from IE3 to IE4, and compared this with the material used in the generation capacity to make up for the additional energy losses of the IE3 motor. Comparing the figures shows that the environmental balance favours continuing efforts to improve energy efficiency in electric motors.

Keywords: motor efficiency, MEPS, greenhouse gas emissions, land use, material use, renewable generation capacity, life cycle assessment, material balance

1 A Common Misconception

Over the past few years, various EU regions have lived through periods of abundant renewable electricity production combined with limited flexibility in demand, leading to negative day-ahead electricity prices. In the spring of 2023, the day-ahead electricity price in the Netherlands dropped as low as -500 €/MWh [1]. These short-lived phenomena gave rise to the common misconception that EU power generation will soon be entirely renewable and free of greenhouse gas (GHG) emissions, leading to the false conclusion that improving energy efficiency in electrical systems is no longer worth its additional material use and associated environmental impact. This argument is most often evoked when discussing investment in the energy performance of long-lasting devices such as motors (typically 20 years) and transformers (typically 40 years). The thinking behind this is that the anticipated energy efficiency improvements will be overtaken by the electricity mix being decarbonized during the lifetime of the device and so will not bring significant environmental benefits.

We counter these misconceptions and calculate the GHG emissions, land use and material use of every MWh/year of electricity in the EU between 2025 and 2045, a 20-year period corresponding with the typical life-time of devices such as medium power electric motors.

2 The Electricity Mix and its impact

To assess the environmental impact arising from the consumption of 1 MWh/year of electricity, various sets of input data are to be combined. The first is the mix of the different types of generation systems used to produce electricity in the EU, as well as the predicted evolution of this mix during the years under scrutiny (2025 to 2045). The second set of input data are the bills-of-material (BOMs) and life-cycle impact (LCI) figures for each of the various types of generation systems forming part of in the electricity mix. We chose to use only publicly available figures for all input data.

The evolution of the electricity mix was found in the European Commission document 'Stepping up Europe's 2030 climate ambition – Impact Assessment' [2], which estimates how the EU electricity mix between 2025 and 2050 is likely to evolve (see Fig. 1). Making abstraction of minor capacity additions in natural gas, hydro and other renewables, the average additional generation capacity mix between 2025 and 2045 will consist for 56% of offshore wind turbines, for 15% of offshore wind turbines, and for 28% of solar PV capacity.

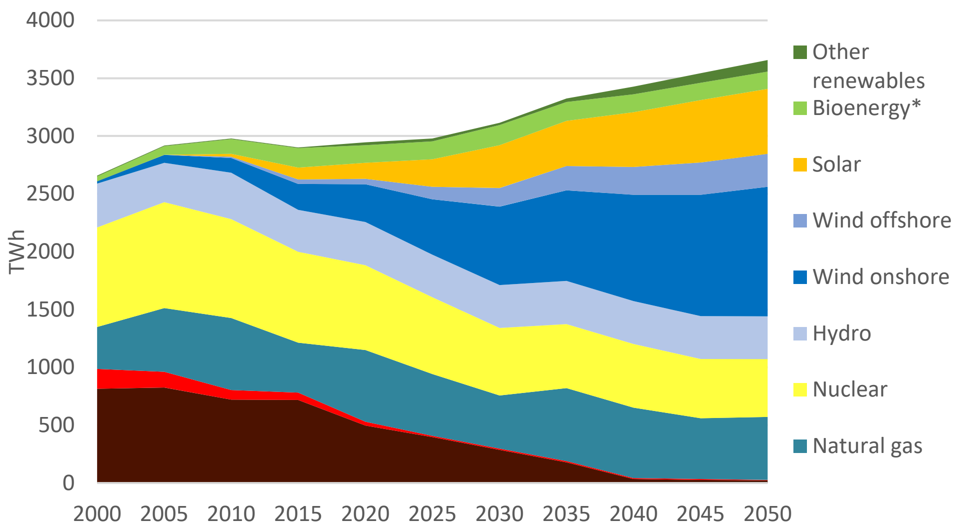

Fig. 1. The evolution of the EU electricity mix as published in the impact assessment of 'Stepping up Europe's 2030 climate ambition' ([**¡Error! Marcador no definido.**] Figure 28).

The total material use per unit of generation capacity was obtained from the 'Renewable Energy Materials Properties Database (REMPD)' curated by the U.S. Department of Energy (DOE) [3]. To translate the generation capacity into an annual electricity production figure, its lifespan and annual productivity in full load equivalent (FLE) is needed. We obtained these figures from the ENTSO-E Power Statistics [4], which indicate an annual productivity of 2076 hrs FLE and lifespan of 20 years for onshore wind turbines, an annual productivity of 3214 hrs FLE and lifespan of 25 years for offshore wind turbines, and an annual productivity of 1200 hrs FLE and life span of 25 years for solar PV plants. This resulted in the bills of material for onshore wind, offshore wind and PV as shown in Table 1.

Table 1. BOMs per annual electricity production for onshore wind, offshore wind and PV [3 and 4], and for the additional generation capacity mix in the EU between 2025 and 2045 [2].

Material category	**Onshore wind (kg/kWh)**	**Offshore wind (kg/kWh)**	**PV (kg/kWh)**	**EU marginal mix (kg/kWh)**
Concrete	0.389	0.000	0.032	**0.227**
Road aggregate	0.590	0.000	0.000	**0.331**
Steel	0.138	0.137	0.048	**0.112**
Composites and polymers	0.028	0.009	0.015	**0.021**
Cast iron	0.012	0.005	0.016	**0.012**
Other metals and alloys	0.018	0.011	0.035	**0.022**
Other materials	0.003	0.001	0.090	**0.027**
Total	**1.178**	**0.163**	**0.236**	**0.752**

The last set of input data are the life-cycle impact (LCI) figures in terms of GHG emissions and land use for each of the various types of generation systems forming part of in the electricity mix. Those figures were obtained from the United Nations Economy Commission for Europe (UNECE), in particular Table 14 in the 2022 document 'Carbon Neutrality in the UNECE Region: Integrated Life-Cycle Assessment of Electricity Sources' [5].

The final calculations combined all of these input data.

3 The Material Use, GHG Emissions and Land Use of EU Power Generation

The additional generation capacity needed to cover energy losses implies material use. Starting from the average additional generation capacity mix between 2025 and 2045 introduced before and the BOMs for the various types of generation systems as given in Table 1, we calculated that consuming 1 MWh of electricity per year in the period from 2025 to 2045 would correspond to an average of **752 kg of material use**, all materials combined, of which **146 kg would be metals** (see column 5 in Table 1).

Using the same projection for the electricity mix, combined with the life-cycle impact date from UNECE, we discerned that 1 MWh/year of electricity consumption between 2025 and 2045 will lead to an average of **146 kg of CO_{2eq} emissions per year**. This figure might seem surprising, since the EU's capacity for renewable power generation has been rising steeply over the past ten years and is expected to continue to grow in the years to come. But, despite this fast-moving transition, generation from coal-fired power plants is expected to be part of the EU electricity mix until 2040. Added to this, there is the fact that the EU power system is still lacking sufficient large-scale energy storage capacity — and will lack such capacity for some years to come — creating the need for gas fired power plants to fill the momentary gaps between electricity demand and variable renewable production.

Calculations using the same data sets — for the EU electricity mix and for the life-cycle impact of power generation — show that 1 MWh of electricity consumption per year also implies 3453 points of land use on average in the period between 2025 and 2045. Land use points are a standardized impact category of a Life Cycle Assessment, expressed in this way to allow comparison between various types of land use that impact the land in a different way. The relation between land use points and land coverage for different types of land use is expressed in Table 32 of [5]. This table indicates, for example, that 131 land-use points per square metre should be taken into account when comparing a particular type of land use to non-irrigated cropland. Consequently, we can conlude that the 3453 points of land use of 1 MWh per year correspond to **26.36 m^2 of non-irrigated cropland**. Note that these land use points only take the competition for land with other activities and certain aspects of biodiversity into account, and not the impact on the landscape and how it is perceived by EU citizens. The construction of renewable generation plants often triggers local protest, and the final share of renewable energy capacity needed for the energy transition will be the most difficult to realize — the low hanging fruit will have been picked and the more difficult and controversial locations will have to be unlocked. Energy efficiency improvements reduce the need for this capacity.

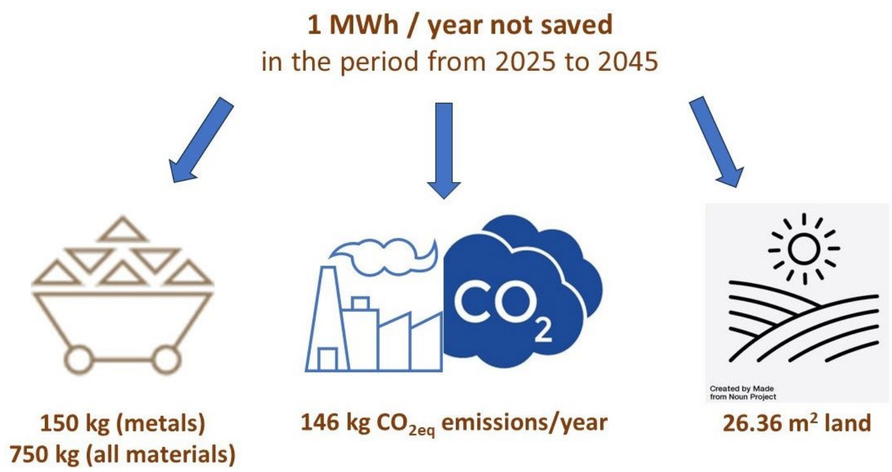

Fig. 2. The average impact of 1 MWh of electricity per year in terms of material use, GHG emissions and land use over the period from 2025 to 2045 in the EU.

4 The Material Balance for Electric Motors

To evaluate the material balance at system level of an energy efficiency upgrade for medium power electric motors, we considered an upgrade from IE3 to IE4 for typical 4-pole 11 kW and 110 kW motors. This efficiency upgrade requires additional metals to manufacture the motor, but the associated energy savings lead to metal savings in power generation. Which of these will be dominant? Note that we will ignore the materials other than metals, as they are less affected by efficiency upgrades and are also considered to be less critical for the energy transition [6].

Table 2 is a representative bill-of-materials for metals used in manufacturing 11 kW and 110 kW motors with IE3 efficiency. Table 2 is a representative bill-of-materials for metals used in the same motors with IE4 efficiency. Comparing Table 2 and Table 3, we see that the extra metals needed in an 11 kW induction motor to upgrade from efficiency IE3 to IE4 is 30 kg. The extra metals needed for a 110 kW induction motor to upgrade from efficiency IE3 to IE4 is 93 kg.

Table 2. Bill of materials of typical 4-pole, 50 Hz, 11 kW / 110 kW IE3 induction motors [7].

Material	11 kW (kg)	110kW (kg)
Electrical steel	70.00	460.00
Other steel	11.60	80.00
Cast iron	41.00	330.00
Aluminium	4.45	24.20
Copper (winding)	13.70	71.60
Copper (leads)	0.18	1.49
Total metals (without packaging)	**140.93**	**967.29**

Table 3. Bill of materials of typical 4-pole, 50 Hz, 11 kW / 110 kW IE4 induction motors [8].

Material	11 kW (kg)	110kW (kg)
Electrical steel	93.10	539.00
Other steel	12.20	83.30
Cast iron	41.00	330.00
Aluminium	4.95	27.10
Copper (winding)	19.30	79.80
Copper (leads)	0.18	1.49
Total metals (without packaging)	**170.73**	**1060.69**

The 11 kW IE3 motor (4-pole, 50 Hz) has an efficiency of 91.4%, compared to 93.3% for the equivalent IE4 motor [9]. This results in a difference in energy losses of 245 W, corresponding to an annual energy consumption of 0.86 MWh, assuming an annual operational time of 3500 hours FLE. This energy consumption means that 275 kg of material is needed to build the required generation capacity, or 53 kg of metals.

The 110 kW IE3 motor (4-pole, 50 Hz) has an efficiency of 95.4%, compared to 96.3% for the equivalent IE4 motor [9]. This results in a difference in energy losses of 1078 W, corresponding to an annual energy consumption of 3.77 MWh, assuming an annual operational time of 3500 hours full load equivalent. This energy consumption means that 2835 kg of material is needed to build the required generation capacity, of which 550 kg are metals.

Table 4 summarizes the difference in material use between an IE3 and an IE4 motor at the level of the motor itself and when considering the overall electrical system. This clearly demonstrates the material balance: despite IE4 motors being heavier than their IE3 counterparts, they save substantial amounts of material when considering the overall electrical system, both in terms of metals and when considering all materials combined.

Table 4. Summary of material use in a IE4 motor compared to its IE3 counterpart.

IE4 compared to IE3	11 kW (kg)	110kW (kg)
Manufacturing (metals)	+ 30	+ 93
Generation energy losses (metals)	- 53	- 550
Total metals	**- 23**	**- 457**
Manufacturing (all materials)	+ 30	+ 93
Generation energy losses (all materials)	- 275	- 2835
Total all materials	**- 245**	**- 2742**

5 Summarizing the Environmental Balance

Fig. 2 summarizes the impact of 1 MWh of electricity per year that is not saved in terms of GHG emissions, land use and material use for the period from 2025 to 2045. In general, these figures demonstrate that efforts to garner additional energy savings still make sense today, as well as in the years to come. More specifically, they allow for comparison with the impact of energy efficiency improvements in electricity end-use applications.

Making such a balancing exercise for the material use caused by a switch from IE3 to IE4 for 11 kW and 110 kW induction motors, we see that the increased material use in the motors caused by the efficiency upgrade is clearly outweighed by the reduction in material use for generation capacity due to the reduced energy losses.

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