INCREASED MATERIAL FOOTPRINT

A potential side-effect of progress towards SDG 7

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EES-2024-715

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Report: EES-2024-715
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Abstract

In 2015, the United Nations introduced the Sustainable Development Goals (SDGs) as a part of the 2030 agenda, aiming for sustainable development by, prioritising human well-being, economic prosperity, and environmental protection. SDG 7, which focuses on ensuring access to affordable, reliable, sustainable, and modern energy for all, requires significant progress as projections indicate that if current trends continue, globally 660 million people will still lack access to electricity by 2030. However, increasing electrification rates, particularly in developing regions, carries the yet unknown risk of amplifying material extraction, thereby impeding efforts toward the sustainable management and efficient utilization of natural resources (SDG 12.2). This study quantifies the trade-off between SDG 7 and SDG 12.2 by calculating the direct and indirect material use associated with reaching a 100% global electrification rate (SDG 7) by 2030. We find that achieving SDG 7 will increase the material footprint of the global electricity sector by 17.2% and achieving SDG 7 with low-carbon electricity sources adds an additional 6.9% increase in material footprint. The majority of the increased electricity demand is projected to occur in Africa and Asia-Pacific, with most material extraction likely to take place in Africa. Despite this, the electricity sector's overall contribution to the global material footprint remains relatively low for all examined materials, resulting in a minimal impact on global material extraction rates. Our study contributes to the literature on trade-offs between the United Nations SDGs and we highlight the potential for locally-produced electricity to benefit communities not only through access to electricity but also through economic gains from the entire supply chain.

1 Introduction

In 2015, the United Nations (UN) introduced the Sustainable Development Goals (SDGs) as a part of the 2030 agenda, aiming for sustainable development by, prioritising human well-being, economic prosperity, and environmental protection [1]. As we approach the midpoint of the 2030 timeline, the progress towards achieving the SDGs is reported to fall short [2]. Among the SDGs requiring urgent acceleration is SDG 7, which focuses on ensuring access to affordable, reliable, sustainable and modern energy for all [1]. Despite an increase in the global population with access to electricity, reaching 91 percent in 2021, approximately 675 million people still lack this basic necessity –an amount equivalent to 1.5 times the EU population–. Particularly, in sub-Saharan Africa over 50% of the population remains without access to electricity [3]. Projections indicate that if the current trend continues, globally 660 million people will still lack access to electricity by 2030 [2].

The UN aims to harmonize all individual SDGs. However, this ambition remains challenging as actions to make progress towards one goal could impede progress in others [4]. For instance, efforts to achieve SDG 7 can lead to a mixture of synergies and trade-offs for other SDGs. While, increasing the electrification rate can positively impact education (SDG 4) and healthcare (SDG 3), it can create challenges towards sustainable consumption and production patterns (SDG 12)[5]. In particular, increasing the electrification rate, particularly in developing regions, carries the risk of amplifying fossil fuel extraction, thereby impeding efforts toward the sustainable management and efficient utilization of natural resources (SDG 12.2) [6]. In response, SDG target 7.2 aims to scale up the share of renewable energy sources in the global energy mix to mitigate carbon emissions. However, the transition to low-carbon electricity generation technologies introduces new challenges, such as the extraction of critical rare earth metals, such as aluminum, copper, nickel, lead and silver which are essential for renewable energy technologies [7, 8, 9].

SDG 12.2 can be measured by calculating material extraction footprints [10]. The material footprint (MF) measures the extraction of materials, along the global supply-chain as a result of global consumption. Various researchers have employed the MF methodologies to identify the effect of changes in global and regional energy transitions on material extraction [7, 8, 9]. The latest International Energy Agency (IEA) report on material scarcity [11], indicated that extraction of raw materials is likely to become a crucial bottleneck to a transition to low-carbon electricity generation [12]. Moreover, several studies have investigated how a transition to a low-carbon energy system affects the material footprint. These papers have studied material extraction in combination with socio-economic scenarios [8], depletion of metal reserves [13], specific material use [14], material vulnerability for EU countries [7], material extraction in combination with capital goods [15] and criticality [9, 13], all within low-carbon energy system scenarios. However, no study investigated the direct trade-off between reaching SDG 7.1 and 7.2 and the associated MF (SDG 12.2). This study addresses this gap by quantifying the direct and indirect material use related to reaching a 100% global electrification rate (SDG 7) by 2030.

To calculate the MF, we employ an environmentally extended regional input-output (EE-MRIO) approach. This methodology links detailed trade data in monetary units to country-specific environmental pressures, like material extraction [16, 17]. The EE-MRIO approach allows the calculation of upstream and indirect material use associated with the downstream final demand, like electricity consumption [18]. We quantify the global material footprint associated with the required additional electricity generation and capital investments to ensure an electrification rate of 100% for the projected global population in 2030. We employ three scenarios: (a) a business as usual (BAU) scenario, where the projected population increase is taken into account, but the electrification rate remains constant; (b) the SDG 7.1 current electricity mix scenario, where needed extra electricity generation capacity is based on the current electricity generation mix in a country, hereafter called the fossil fuel scenario; (c) the SDG 7.1 & 7.2 low-carbon scenario, where all additional electricity is generated by renewable electricity generation technologies based on projections by Jacobson et al. [19, 20], hereafter the 100% renewable scenario (table 1).

The use of the EE-MRIO database EXIOBASE allows us to exogenously change the final demand of electricity consumption produced by 11 distinct electricity generation sectors (coal, gas, nuclear, hydro, wind, petroleum and oil derivatives, biomass and waste, solar photovoltaic, solar thermal, tide wave and ocean, and geothermal) for each country [21]. Furthermore, we investigate the MF for the extraction of the metals nickel, zinc, lead, copper, aluminium, other non-ferrous metals (ONM) and platinum group metals (PGM). The depletion of these metals is reported to be critical in the energy transition and is provided by the EXIOBASE dataset [7, 8, 12, 13, 22]. In this work, we include direct and indirect material use associated with an increase in electricity demand. The direct material use refers to the metals used directly in the generation of electricity, while indirect use refers to materials used elsewhere in the economy, for example, materials needed for constructing the machinery that is used in the maintenance of a power plant.

2 Methods

2.1 EE-MRIO model

We use an EE-MRIO model to capture all direct material extraction (material use related to the electricity generation sectors) and indirect material extraction (occurring in upstream supply chains and with capital investment) related to the 2030 scenarios. The EE-MRIO methodology links environmental data to all financial transactions within economic sectors in different countries. An EE-MRIO model is defined by an intermediate (Z-matrix) and final demand matrix (Y-matrix) based on national statistical accounts. The Z-matrix, with the dimensions (mn) x (mn), explains the interdependence between different economic sectors (m) and countries (n) by defining monetary flows that are captured in the Z-matrix of the dimensions (mn) x (mn). Z_{ij}^{rs} represents the monetary flow from sector (*i*) in region (*r*) to sector (*j*) in region *s* [16, 23, 17]. With the use of equation

$$A = Z \times X^{-1} \tag{1}$$

where Z is the interdependence matrix and X is a sector's total output, the technological coefficient matrix A can be calculated. Subsequently the the A matrix can be transformed to the Leontief inverse which encompasses both direct and indirect input requirements to fulfil one unit of a sector's output in monetary terms and is denoted as:

$$x = (I - A)^{-1} \Delta Y \tag{2}$$

where A is the inter-industry technological coefficient matrix, I is the identity matrix and ΔY is the estimated change in final demand related to an increase in electricity demand between the baseline year and 2030 [16, 18](see supplementary information). To integrate the material extraction to equation 2, the material extraction intensity (e_j^s) which gives the material extraction per monetary output of an economic sector (s) in a country (j), is stored in a column factor and diaganolised into a matrix (E). By multiplying equation 2 with the E-matrix, the material footprint (MF) associated with the change in a sector's final demand is integrated, resulting in:

$$MF = E \times (I - A)^{-1} \Delta Y \tag{3}$$

Once these underlying algebraic methods have been applied, future scenarios are implemented as exogenous changes in final demand (ΔY), based on population expectations, changes in expected electricity demand and the type of electricity generation technology. The EE-MRIO model then provides the MF per sector per country associated with the exogenous change in final demand. We splitted the material extraction associated with electricity generation in two parts: (a) materials associated with the generation of electricity (fuels, operation and maintenance), hereafter FOM, are introduced in the EE-MRIO model as household and governmental final demand, and (b) the capital investments related to the installation and manufacturing of new electricity generation facilities, which is introduced as Gross Fixed Capital Formation (GFCF).

2.2 Scenarios

We analysed three global electricity demand scenarios for 2030. The starting point for the scenarios was the electricity demand in 2015 as provided by EXIOBASE 3.8 [21], which we endogenously changed to analyse 2030 scenarios. The 2030 scenarios are based on the expected population projections [24] and the progress to be made to reach SDG 7 in 2030 [3]. We have made the assumption that the electricity consumption in 2015 remains constant and calculated the increase in electricity is solely dependent on the increase in population and progress towards SDG 7.

The electricity generation mix of the additionally required electricity to reach SDG 7 in the 100% renewable scenario is based on an end-state scenario of Jacobson et al. [19] to reach the Paris climate target with electricity generated by wind, solar, tidal and wave, geothermal and hydropower. The energy generation scenario as reported by Jacobson et al. [19] is optimized for 143 countries and matches total energy demand including energy storage. Moreover, it is mainly based on currently commercially available generation sources as solar, wind, hydropower, and geothermal technologies [20]. We applied this electricity mix for the additional electricity. As we only focus on the additional electricity to reach SDG 7 and assume the 2015 base load remains unchanged, we did not include any energy storage in our scenario. Our scenarios focus on the capital investments in new electricity generation plants and the annual fuel, operation and maintenance in reaching SDG 7. However, it does not include the distribution of electricity and the substitution of other energy types. For example, the potential substitution of wood-based cooking systems to electric systems which could reduce the extraction of wood, is not included in our research. Moreover, we do not take into account any increase or structural changes in electricity demand, efficiencies and technologies due to socio-economic changes in the future. Table 1 shows the characteristics of and differences between the scenarios and figure 2 shows the electricity generation mix for the scenarios.

	BUA scenario	Fossil fuel scenario	100% renewable scenario
Population projection for 2030 included in expected electricity demand	Yes	Yes	Yes
Electrification rate (progress SDG 7)	91.4% [3]	100%	100%
Electricity mix 2030	Based on current electricity mix provided by EXIOBASE [21]	Based on current electricity mix provided by EXIOBASE [21]	Based on low-carbon projections by Jacobson et al. [19]

Table 1: Difference between business as usual, fossil fuel and 100% renewable scenario. (Bank [3];Jacobson et al. [19];Stadler et al. [21])

The EXIOBASE dataset contains 163 economic sectors in 44 countries and 5 rest of the world (r.o.w.) regions. The final demand matrix (Y) consists of 6 final demand categories of which households, government, and gross fixed capital formation (GFCF). As the majority of the countries with limited electricity access are located in the EXIOBASE r.o.w. regions and therefore lack country-specific data, we first use the spatially disaggregated EXIOBASE data published by Cabernard and Pfister [25] (see supplementary information for more information). The disaggregated EXIOBASE is based on the EORA26 dataset and contains 189 countries (m) and 163 economic sectors (i), and the most recent year is 2015 (t=0). To calculate the increase in electricity demand for the 2030 scenarios, we select the electricity generation sectors and multiply the household and government final demand (f) consumption of the electricity generation sectors ($\hat{\imath}$) at t = 0 with the expected population growth per country (p^r) [24]. We assume a proportional increase in household and government final demand with population growth, as government spending, covering domains like public infrastructure and defence, is projected to grow linearly alongside population projections [15, 26]. This results in the baseline increase (scenario C) in the final demand factor ($\Delta y^r_{\hat{\imath}}$) for a specific electricity generation sector ($\hat{\imath}$) in a country (r):

$$\Delta y^r_{\hat{\imath}} = f_{\hat{\imath}} \times p^r \tag{4}$$

For determining the electricity demand for 2030 where SDG 7 is achieved (scenario a and b) an additional increase in household final demand for electricity for each country is calculated based on the country's share of the population lacking access to electricity in 2015 (The World Bank, 2023 [3]). The electrification rate refers to the ability of end users to consume electricity and have electricity for more than 4 hours per day [27]. The additional electricity is calculated by

$$\Delta y_{\hat{\imath}}^{r} = f_{\hat{\imath}} \times p^{r} \times ((1/w) - 1) \tag{5}$$

where, ($f_{\hat{\imath}}$) is a country's final household demand of a certain electricity source ($\hat{\imath}$), the (p^{r}) is the expected population growth per country, and (w) is the fraction of population with electricity in 2015. The several final demand factors ($\Delta y_{\hat{\imath}}^{r}$) created in equation 4 and 5 for households and government are stored in a column vector and aggregated back to the country resolution of EXIOBASE 3.8 to create the final demand matrix (ΔY) with 44 countries and 5 r.o.w regions.

2.3 MRIO model - materials associated with fuel, operation and maintenance

For calculating the material footprint associated with the fuel, operations and maintenance (FOM) for the baseline scenario, we can introduce the increase in final demand as calculated in equation 4 to the MF equation (Eq. 3). Subsequently, for the BUA scenario, we can introduce the increase in final demand as calculated in equation 5 to the MF equation (Eq. 3).

For the 100% renewable scenario (B), the additional final demand required in 2030 must be allocated among the electricity generation sectors ($\hat{\imath}$) based on the 100% renewable scenario outlined by Jacobson et al. [19, 20], which requires an additional processing step. While the final demand offers insights into the yearly monetary consumption of electricity generation, it lacks information per unit of electricity generated, essential for restructuring the final demand matrix. For instance, wind-generated electricity may entail lower monetary output compared to coal-generated electricity, while producing more electricity. Consequently, although the monetary value of the final demand for coal may exceed that of wind in a given country, wind-based electricity consumption could be higher. Therefore, the monetary values are first transformed into energy supply in terajoules (TJ), by using the energy intensity data for each sector as provided by EXIOBASE 3.8. Subsequently, we calculated the total final demand (in TJ) per country and divided this total over the electricity generation sectors according to the renewable scenario outlined by Jacobson et al. [19, 20] (see supplementary information). Afterwards, we transformed the energy final demand back to monetary values by dividing the FD (in TJ) with the energy intensity coefficients of EXIOBASE. As for certain countries new electricity generation technologies are added to the electricity mix, some energy intensity coefficients were not present in the EXIOBASE dataset. In this situation we opted a similar strategy as published by [28] and replaced these missing values by the energy intensity of the same electricity generation sector value of a comparable country (see Supplementary Information). We judged the comparability of the countries based on close geographical proximity and a comparable economic structure. Afterwards, we introduced the final demand factors to equation 3 to calculate the material footprint associated with FOM.

2.4 MRIO model - materials associated with capital investments

Once the additional required electricity demand (captured in $\Delta Y^{a}, b, c$) for all scenarios is calculated, it is introduced to the input-output table (equation 2 to compute the necessary increase in yearly total output (in monetary values) per electricity generation sector ($\Delta X_{\hat{\imath}}$) for all countries [9]. To calculate the installation of new capacity (GFCF), we again transform the monetary final demand vectors to energy units by multiplying them with the energy intensity data for each sector as provided by EXIOBASE 3.8. Then we convert the required energy per sector from TJ to MWH and introduce it to equation 6:

$$GFCF_{\hat{\imath}}^{r} = CAPEX \times \frac{MWH}{capfator * 8760h} \tag{6}$$

where CAPEX (in €/MW) is based on projections for the CAPEX in the European Union published in the 2014 Energy Technology Reference Indicator (ETRI) report by Carlsson et al. [29]. Afterwards, we distribute the GFCF vectors per technology over the different sectors in EXIOBASE based on the detailed breakdown for each electricity sector published by Černỳ et al. [28] (see Supplementary Information). The GFCF vectors are then multiplied with the pre-multiplied Leontief matrix (Equation 3), enabling the identification of all material extractions associated with capital investment for all scenarios.

2.5 Data

In this work, we chose EXIOBASE 3.8 ([21]) over other EE-MRIO models as it includes 11 electricity sectors and has a high data availability on material extraction. EXIOBASE 3.8 includes 44 countries and 5 r.o.w. regions. Population growth projections were sourced from the United Nations [24], while electrification rates and progress towards SDG 7 were derived from the World Bank [3]. These data points were disaggregated to the extended EXIOBASE version provided by Cabernard and Pfister [25] to calculate the country-specific increases in final demand. The data on the CAPEX and the capacity factor to calculate the MF associated with the GFCF is obtained from the Energy Technology Reference Indicator report by [29] (2014) and from the International Energy Outlook 2016 by IEA [30], respectively.

2.6 Data limitations and uncertainties

In this work, we also encountered challenges as a result from the nature of the EE-MRIO analysis. First of all, the spatial resolution and especially the lack of country-specific information in the r.o.w. regions did not allow us to identify any country-specific deviations in MF for these regions. To calculate the increase in electricity consumption for each country in the r.ow. region we had to use the spatially disaggregated EXIOBASE, which only provided data until 2015. Subsequently, as the disaggregated EXIOBASE dataset did not provide any information on the material footprints, the r.o.w. had to be aggregated again after creating the final demand vectors. Hence, information on the supply chain of the aggregated r.o.w. countries, material intensities of the sectors in these countries and international trade within the r.o.w region is not taken into account in this work. This high level of aggregation in r.o.w regions is a problem as high and low-impacting countries are aggregated into one region [31, 32].

Secondly, we relied on EXIOBASE 3.8 data from 2015 to estimate the increase in electricity demand for each country within the r.o.w. regions. While utilizing more recent EXIOBASE data would have been ideal, our approach provides a quantification of the MF necessary to achieve SDG 7 by 2030, using 2015 as the starting point. It is crucial to consider that significant techno-economic developments have likely occurred and will occur in the electricity sector between 2015 and 2030 [33]. Technological improvements, shifts in global trade patterns, and changes in supply chains and material intensities are expected over the years, introducing higher uncertainty as the timeline extends beyond 2015. This uncertainty is especially pertinent for emerging technologies such as tidal and wave energy, and geothermal power [28]. As such, conclusions regarding the MF that focus only on the latter part of 2015-2030 and take into account newer technologies should be approached with caution.

A third uncertainty originates in the calculation of the MF related to the installation of new capacity (GFCF). Data on the capacity factor [30] was only present for aggregated regions, i.e. Africa or Europe. Variability in capacity factor between countries within a continent is therefore not taken into account. Moreover, as worldwide data on country and electricity sector-specific CAPEX was not present, we assumed a similar CAPEX for all countries [29]. However, the CAPEX is country-specific and the CAPEX for the same electricity sector can differ strongly between countries [33]. The most recent World Energy Outlook [33] reported a difference in CAPEX between countries of more than 100% for a nuclear power plant. In general, it can be expected that the CAPEX is lower for less developed countries compared to wealthy countries [34][35]. As the additional electricity demand is predominantly located in developing countries, this results likely in an overestimation of the MF. Sensitivity analysis of the CAPEX indicated that a 1% increase in CAPEX results in an equal increase in the MF for the specific region.

3 Results

To demonstrate the effect of making progress toward reaching SDG 7 on the material footprint, we present three 2030 scenarios with corresponding results. Our study distinguishes between MF related to operational processes including the use of fuels, operations and maintenance and the MF associated with the construction and installation of the electricity production facilities. By using the EE-MRIO methodology upstream and embodied materials are also included in our analysis. More detailed results are provided in the supplementary information.

In 2015, the base-year of our analysis, 954 million people lacked access to electricity, mainly located in sub-Saharan Africa. Figure 1 highlights that countries with a low electrification rate and thus a substantial gap towards SDG 7 are predominantly located in sub-Saharan Africa. Conversely, India stands out in terms of the absolute number of people without access to electricity due to its large population (figure 1). Countries in North America and the EU27 + UK show no share of the population without access to electricity.

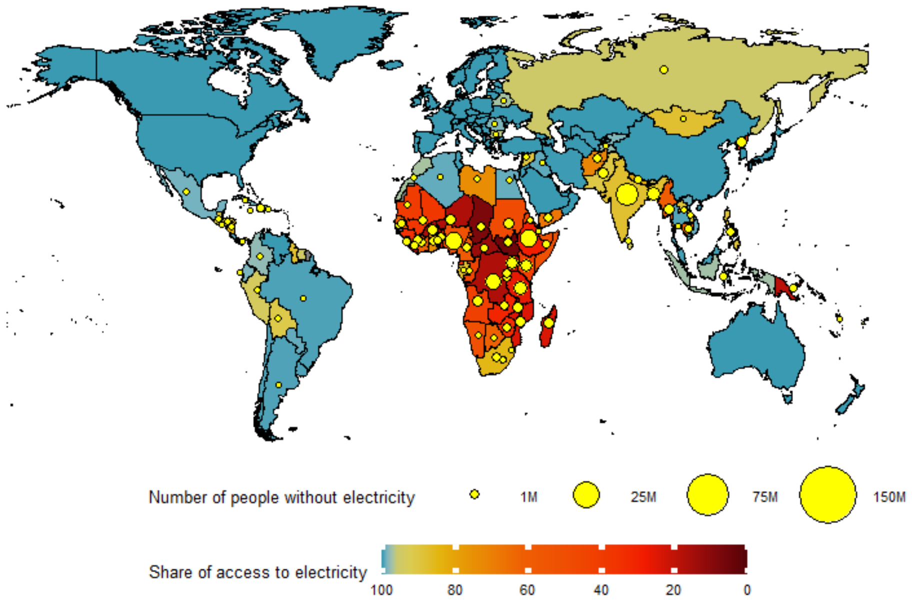

Figure 1: Progress towards SDG 7- The electrification rate and the absolute amount of people having no access to electricity.

The additional electricity required to meet 2030 demand in each scenario can be attributed to either an expected growth in population increase or achieving SDG 7. In the BAU scenario, all additional electricity demand can be attributed to the increase in expected population, while for the fossil fuel and the 100% renewable scenario, the additional electricity to meet SDG 7 in 2030 is included. Figure 2 shows that the majority of the increase in electricity is concentrated in Africa, Asia-Pacific and in North America. In Africa and Asia-Pacific, this demand is primarily due to the significant population lacking electricity access, whereas for other regions the increased demand is mainly related to the expected population increase by 2030. The total additional electricity demand compared to the total electricity demand in 2015 to ensure universal access in Africa and Asia-Pacific is 240.3% and 18%, respectively. The increase in electricity demand in North America and EU27 + UK is only related to the expected increase in population from 2015 to 2030. Specifically, North America's substantial increase in electricity demand can be attributed to an expected 8% population rise combined with relatively high electricity consumption levels from the base year. Furthermore, our analysis shows that in the fossil fuel scenario, Africa predominantly relies on gas-based electricity, while Asia-Pacific is more reliant on coal-based electricity. The 100% renewable scenario shows for all continents a comparable electricity mix, with predominantly electricity generated by wind, solar and hydro.

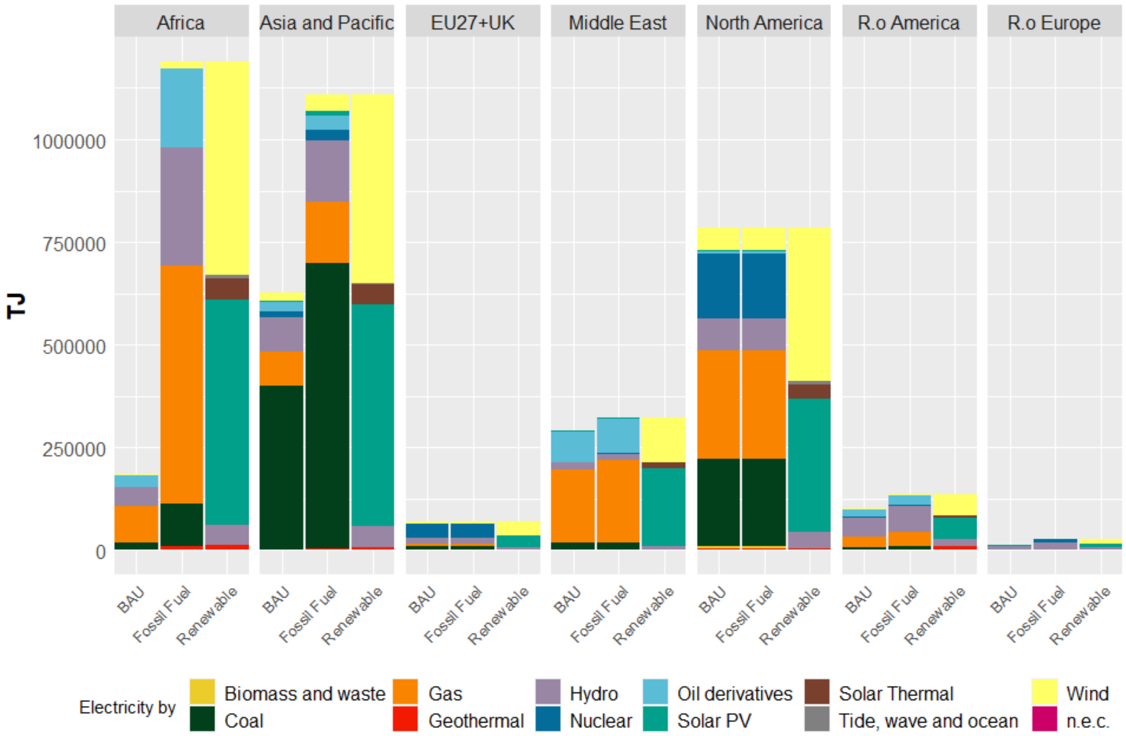

Figure 2: Additional electricity demand per year per continent in terajoule for the BAU, fossil fuel and 100% renewable scenario. R.o = rest of.

3.1 Major material extraction due to increased electricity demand in Africa and Asia-Pacific

By taking a further look at the material extraction resulting from increased electricity demand across continents, our analysis highlights Africa and Asia-Pacific as the regions with the highest material footprint (MF) associated with rising electricity demand. Interestingly, North America shows a relatively low material footprint associated with the FOM, while an increase in electricity demand is expected (see figure 2). This can be attributed to the relatively low material intensity present in the MRIO structure of the value chain of electricity production in the USA and Canada. For lead and zinc a large share can be assigned to the increase in electricity demand in the rest of (r.o) America, which can be assigned to the high material intensity MRIO structure of the electricity production chain in these countries but also to the relative large share of hydro and petroleum and oil-based electricity in the BAU and the fossil fuel scenario. On the other hand, low MF is found in the Middle East, while having a larger additional electricity demand compared to r.o America. This can be explained by a lower material intensity of the electricity generation sectors and the underlying economic structure in the Middle East. Furthermore, in general, the EU and the r.o Europe show a limited MF mainly due to a limited increase in expected electricity demand. Thus, while the EU and r.o Europe are not present, the majority of the material footprint originate from an increase in electricity demand in Africa and Asia-Pacific.

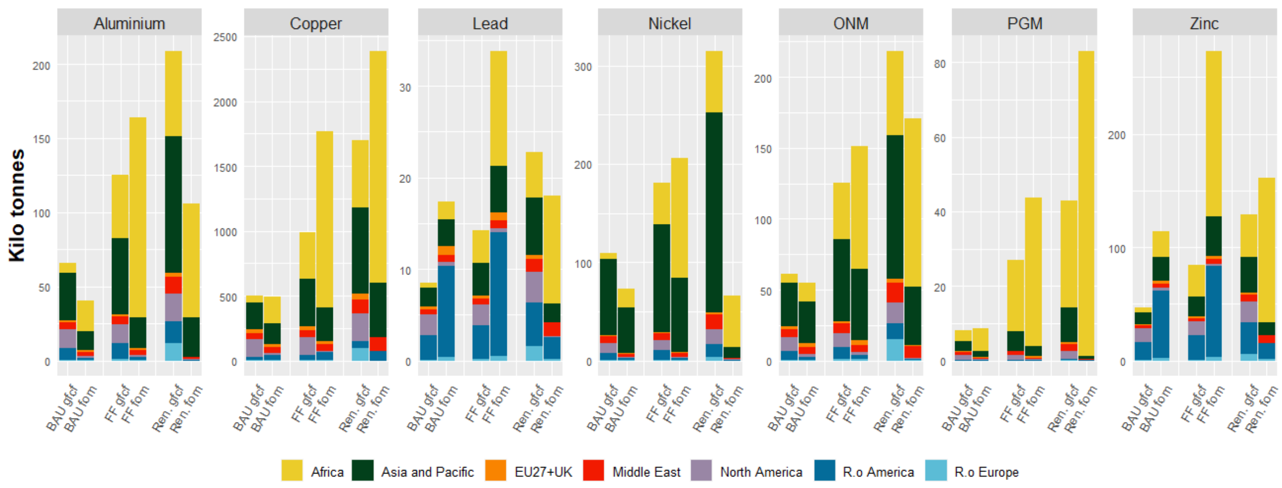

Figure 3: Material footprint and regional contribution - The yearly material extraction associated with the BAU, fossil fuel and 100% renewable scenario. gfcf = Gross Fixed Capital Formation. fom = Fuel, operations and maintenance. R.o = rest of.

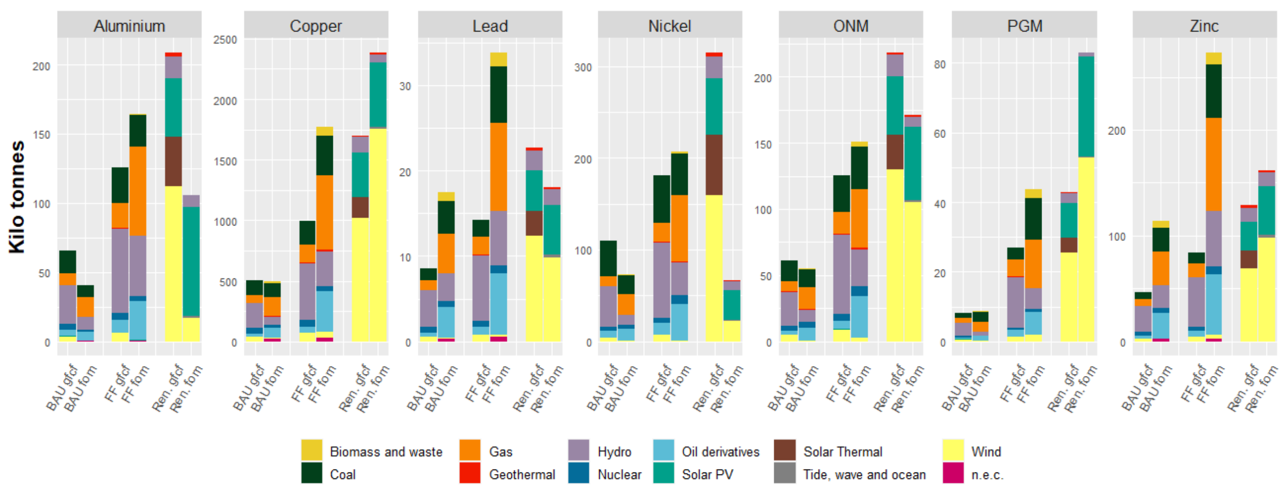

Figure 4: Material footprint and sectorial contribution - The yearly material extraction associated with the BAU, fossil fuel and 100% renewable scenario. gcfc = Gross Fixed Capital Formation. fom = Fuel, operations and maintenance.

3.2 Material footprint switch in renewable scenario

Figure 3 and 4 show that achieving SDG 7 increases the material footprint associated with the FOM and the GFCF for all materials. Additionally, a general trend emerges where the MF associated with capital investments increases in the 100% renewable scenario compared with the fossil fuel scenario. Specifically, there is a doubling of material extraction needed for capital investments. Furthermore, the material footprint associated with FOM decreases for aluminium, lead, nickel and zinc, while the FOM-related MF for copper, other non-ferrous metals and platinum group metals increases. Overall, the trend indicates an increase MF associated with capital investments and a decrease in material extraction from operational processes. It is, however, important to note that the MF associated with capital investments is in our study spread out over the time-frame between 2015 and 2030, while most electricity production facilities are expected to have a longer lifetime and can therefore also be used after 2030.

Additionally, figure 4 highlights that in the fossil fuel scenario, material extraction is primarily attributed to the electricity generation from hydro, gas, coal and oil derivatives. Across the investigated materials in the 100% renewable scenario, the capital investment in wind-based electricity generation stands out as the major contributor to the MF. This can be partially attributed to the substantial share of wind-based electricity in the 100% renewable scenario (see figure 2). However, solar photovoltaic (PV)-based electricity, also prevalent in the scenario, has a smaller impact on material use. Thus, each electricity production sector exhibits unique characteristics in material extraction per MW installation and per MWh electricity production.

This distinction is further explained in figure 5. Material extraction per MW installation represents all the upstream materials associated with the capital investment, while the material extraction per MWh illustrates the materials associated with FOM. Figure 5 illustrates these dynamics for the global yearly material extraction, based on the techno-economic structure of EXIOBASE 3.0, year 2015. Technologies located in quadrant 1 (Q1) show a low material footprint related to the installation and operation processes. Quadrant 2 (Q2) includes technologies with high material extraction during operational processes but relatively lower investment-related extraction such as petroleum and oil electricity production. Quadrant 3 (Q3) shows technologies with high material extraction during both operational and installation phases, exemplified by coal-based electricity production. The lower-right quadrant (Q4) includes technologies with high investment-related material extraction but low operational material extraction. Interestingly, the installation of geothermal electricity plants shows for all materials the highest extraction. Solar PV and thermal electricity generation, located in Q1, demonstrate particularly favourable material footprints due to low extraction associated with both operational processes and investment. Consistent with the high proportion of wind in the 100% renewable scenario (see figure 2), wind electricity production primarily falls into Q4, indicating higher material extraction during installation and lower extraction during operations and fuel usage. Thus, different electricity generation technologies display distinct material extraction characteristics concerning capital investments versus operational processes, fuel, and maintenance.

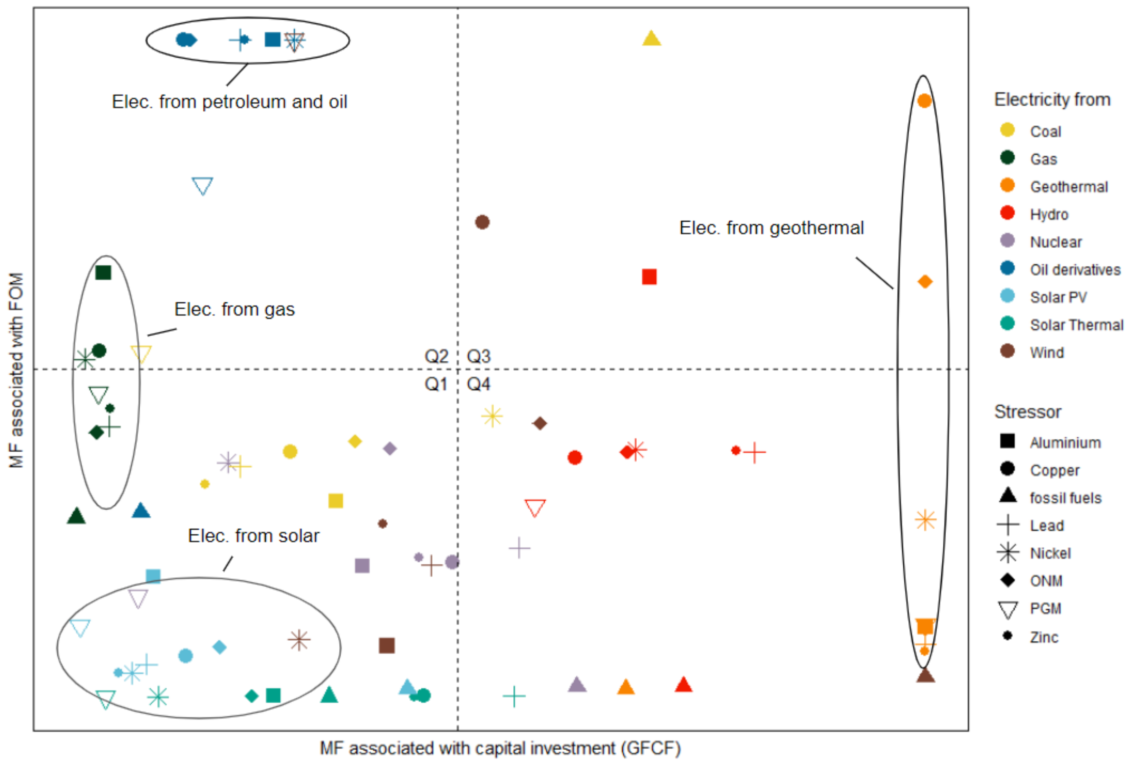

Figure 5: Relative material extraction related to the fuel, operations and maintenance (FOM) and capital investments (GFCF).

3.3 Spatial distribution of material extraction

Figure 6 illustrates the spatial distribution of mining activities in the fossil fuel scenario for 2030. The majority of material extraction occurs in Africa and the r.o America region. However, the geographical distribution of mining activities varies significantly for different materials. For instance, Indonesia hosts the majority of nickel mining operations, while South Africa leads in platinum group metals mining. Additionally, lead and zinc extraction is predominantly concentrated in the r.o America region, whereas copper extraction predominantly occurs in the African region. The extraction of non-ferrous metals shows a less concentrated global distribution. Our analysis shows a general absence of EU27 + UK and the r.o middle east in mining activities.

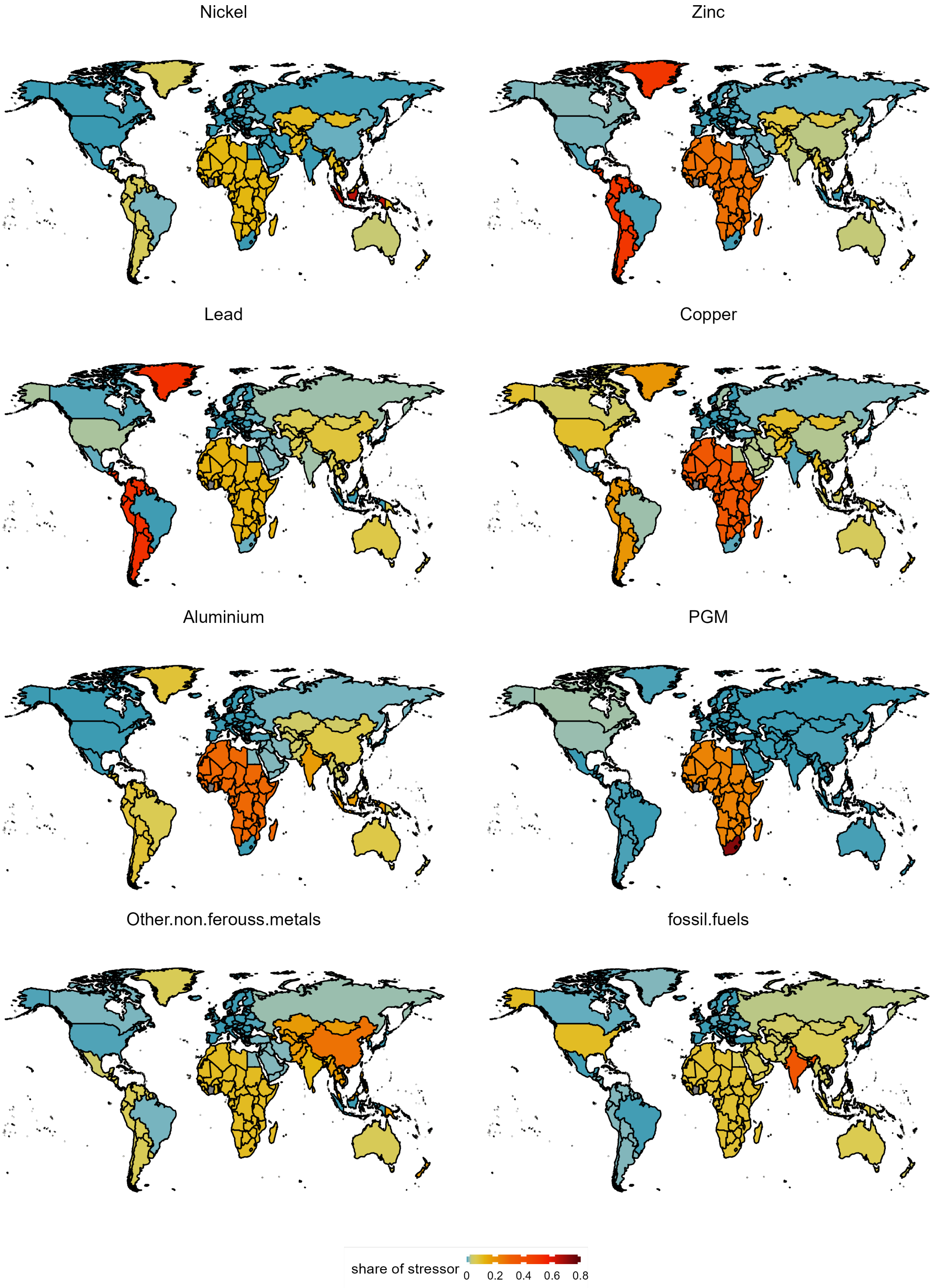

Figure 6: Relative spatial distribution of extraction of materials - The colour scale illustrates the relative share of extraction compared to the total annual extraction.

Overall, our analysis reveals that achieving SDG 7 amplifies the average material footprint (MF) of the electricity generation sectors by 17.2%. When also taking into account the population increase the total MF of the electricity sector increases to 30.3% and transitioning to a 100% renewable energy scenario adds a 6.85% to the electricity sector's MF. Specifically, if the extra electricity required to meet SDG 7 is generated entirely from renewable sources, the MF for aluminum, copper, ONM, and PGM will increase, while the MF for zinc, nickel, and lead will decrease (see Supplementary Results, Table S5). However, when comparing the total MF of electricity generation in 2030 to the total global extraction in 2015, we observe that the sector's relative contribution is less than 1% for all materials (see figure 7 and Supplementary Results Table S4). Thus, the overall contribution of the electricity sector to global material extraction is relatively small.

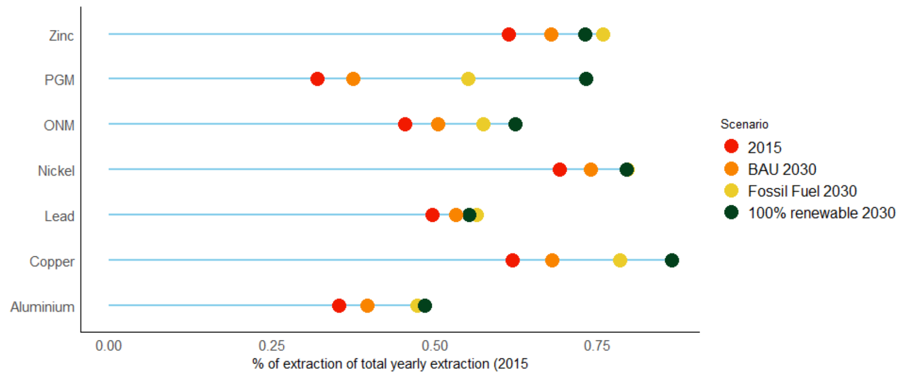

Figure 7: Material extraction of the electricity sector- The material extraction of the 2015 baseline, BAU, fossil fuel, and 100% renewable scenario as a percentage of the total yearly material extraction of the full economy.

4 Discussion

In this work, we show the trade-off between ensuring universal access to electricity (SDG 7) and the sustainable management and efficient utilization of natural resources (SDG 12.2) by 2030. We confirm that achieving SDG 7 increases the material footprint (MF) of the global electricity sector by 17.2%. Moreover, meeting the additional electricity with low-carbon sources further increases material extraction by 6.9%. We identify a trade-off between material use during capital investments and operational phases. Renewable electricity generation technologies require substantial material extraction upfront, whereas fossil fuel-based technologies require more materials during operation and maintenance.

Our study reveals that the majority of the material demand to achieve SDG 7 originates from increased electricity consumption in Africa and Asia-Pacific, driving the extraction across all investigated materials. For lead and zinc, the increased electricity demand in r.o. America plays a role. Conversely, minimal additional electricity demand in Europe results in limited MF associated with these regions. In the context of the fossil fuel scenario, materials essential for capital investments are predominantly sourced from gas, coal, and hydro sources. Operational material footprints, on the other hand, are notably influenced by electricity generation from oil derivatives, reflecting their high material intensity per unit of electricity produced. Interestingly, the capital investment in wind energy emerges as a key contributor to increased material footprints across all materials, consistent with previous research [13, 36, 37]. Overall, solar photovoltaic (PV) and solar thermal technologies exhibit favourable characteristics in terms of material extraction for both capital investments and operations. Despite solar and wind dominating the 2030 electricity mix, solar technologies generally exhibit lower material footprints compared to wind-generated electricity [12].

To our knowledge, this is the first analysis to directly quantify the trade-off between progress towards SDG 7 and material extraction, as suggested by Pradhan et al. [5]. However, consistent with previous research [8, 13], we found that the contribution of the electricity sector to the global MF is relatively small. Under the 100% renewable scenario, we observed an increase in MF for a couple of materials. Especially a large increase in copper, PGM and ONM material extraction is found which is in line with previous research illustrating a significant expected increase when transitioning to low-carbon electricity sources [38]. On the other hand, due to the small share of the electricity sector in the global MF, the direct impact of the transition to renewable is relatively small. This aligns with the findings of Månberger and Stenqvist [36] and Valero et al. [13], who reported that material reserves of copper, nickel, and platinum are unlikely to be depleted due to increased future electricity demand and a transition towards a low-carbon energy system. Our analysis supports that the impact of the electricity sector is relatively small, showing a negligible increase (less than 0.5%) in yearly extraction for these metals under the fossil fuel and 100% renewable scenario associated with achieving SDG 7.

Considering the geographic distribution of mining activities, we observe zinc and lead extraction primarily in the r.o. America region, consistent with global mining data [39]. Africa plays a significant role in mining copper, platinum group metals, and aluminum, while Asia-Pacific leads in other non-ferrous metals extraction. Notably, Indonesia stands out as a key location for nickel mining, aligning with global production trends [39, 40]. Given that a substantial portion of the additional electricity demand for SDG 7 originates in Africa, domestic mining could provide environmental and socioeconomic benefits such as reduced transportation emissions and local economic development [41]. Moreover, studies have reported that shifting from fossil fuels to renewable-based electricity creates jobs [42]. Therefore, while achieving SDG 7 may involve trade-offs with MF and SDG 12.2, it also presents opportunities for fostering positive impacts on local communities and advancing other SDGs. However, technology optimisation is crucial, as there is a potential environmental risk for increased toxicity and carbon emissions with increased mining activities [43]. Additionally, studies indicate that within supply chains, value is mostly not added at the location of the natural extraction but elsewhere in the supply chain [17, 44]. Therefore, promoting local efficient production of electricity potentially offers a more sustainable solution, in which local communities can reap also the benefits from the full supply chain of producing their electricity consumption. Additionally, as it has been reported that the transition to low-carbon electricity sources increases the demand for medium- and high-skilled labour [28], focusing on education in these regions is needed for providing local electricity production. Moreover, despite finding a relatively negligible overall increase in material extraction associated with achieving SDG 7, increases in efficiency of renewable as reported by Diesendorf and Wiedmann [45] and Slameršak et al. [46] could potentially decrease the need for critical materials.

This study focuses exclusively on additional electricity demand to achieve SDG 7, alongside projected population growth. Distribution losses and increased electricity consumption associated with broader socio-economic changes [33] are excluded from our scenarios. Broader macroeconomic models, such as Computable General Equilibrium, could incorporate these impacts [42]. Furthermore, our renewable scenario, lack consideration of electricity storage, crucial for future renewable energy systems [12, 33], potentially resulting in underestimations of material footprints (MF) associated with 100% renewable scenarios, particularly concerning critical materials such as nickel required for batteries [36, 13].

As we worked with scenarios, which are always simplifications of reality, we also found relevant assumptions. First of all, we calculate the amount of additional electricity based on the current electricity demand in a country and multiply this by the population lacking electricity. Hence, we assumed that access to electricity is solely dependent on the generation and production, while Dagnachew et al. [47] reported that the challenge in electrification in Sub-Saharan Africa is not only the lack of electricity generation but mainly a result of governance problems and the lack of investment capital [6]. Secondly, our assumption that all increased electricity demand will be met by newly installed generation plants overlooks the possibility that existing plants may have untapped capacity to meet additional electricity needs. Thirdly, rural areas globally experience lower electricity consumption compared to urban regions [27]. In this work, we base our calculation of additional electricity required to achieve SDG 7 on a country's current total electricity demand, which primarily mirrors urban consumption patterns. Considering that urban areas generally exhibit higher electricity demands than rural areas [47, 48], our projected additional electricity needs may result in an overestimation of the MF associated with achieving SDG 7

Moreover, the capital investments are provided to the EE-MRIO model as an additional economic activity, and therefore, do not consider any substitution in investments. Previous studies have reported that investments in renewables can crowd out investment in other sectors [28, 49] which could indirectly reduce the MF in other sectors and thus result in a potential overestimation of the MF. Moreover, critical materials such as neodymium (used in wind energy), silicon and tellurium (for solar PV), cobalt, and lithium (essential for batteries) are crucial in transitioning towards a low-carbon energy future but are absent from our analysis due to their absence in EXIOBASE 3.8 [41, 38, 50].

5 Conclusion

This study is the first to directly quantify the trade-off between achieving universal access to electricity (SDG 7) and sustainable material resource use (SDG 12.2) by 2030. We found that reaching a 100% electrification rate by 2030 will increase the material footprint of the global electricity sector by 17.2%. Furthermore, supplying the additional future electricity demand with low-carbon sources will raise material extraction of the global electricity sector by an additional 6.9%. Nevertheless, the electricity sector's overall contribution to the global material footprint is relatively low for all examined materials, resulting in a small impact on global material extraction rates.

Additionally, we identified the trend that transitioning to low-carbon energy sources leads to an increased material footprint during the capital investment phase, while the footprint for fuel, operations, and maintenance decreases for most materials studied. Wind turbine installations, in particular, are highly material-intensive initially but require relatively low material extraction during operations and maintenance. Conversely, solar energy exhibits the most favourable material extraction set of characteristics, with minimal impacts both during capital investment and throughout the operation and maintenance phases.

Our analysis indicates that regions such as Africa and Asia-Pacific will see the greatest increase in electricity demand in achieving SDG 7. Given Africa's central role in material extraction and rising electricity demand, optimizing local energy technologies and encouraging local production could reduce environmental impacts while providing significant socio-economic benefits for local communities. However, these potential benefits come with risks. Comprehensive education, efficient electricity and a reorganisation of the supply chain are essential to reduce mining-related environmental pressures and ensure that local communities truly reap the benefits.

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A Supplementary Methodology and data processing

A.1 Regionally extended Exiobase

As the majority of the countries with limited electricity access are located in the EXIOBASE 3.8 r.o.w. regions and therefore lack country specific data, we first use the spatially disaggregated EXIOBASE. Cabernard and Pfister [1] disaggregated the five r.o.w. regions of EXIOBASE 3.4 into 145 countries for the baseyear 2015. Based on country specific data of EORA26 Lenzen et al. [2] each r.o.w region was disaggregated by the corresponding regional share of the country-specific element of EORA26. An example can be found on page 3 in Cabernard and Pfister [1]. Moreover, Cabernard and Pfister [1] created extensions on the EE-MRIO models for land use, water use, biodiversity loss, workforce, climate change impacts, PM health impacts. As the disaggregated EXIOBASE dataset did not provide any information on the material footprints, the r.o.w. had to be aggregated again after creating the final demand vectors.

A.2 Technical coefficients for the renewable scenario

For several electricity generation technologies, As the 2030 renewable scenario of [3] often included electricity generation for countries that were not present in the electricity demand mix of the 2015 baseline, for several countries data on energy and material intensity coefficients were not present. Hence, we replaced the missing intensity coefficients by the energy intensity of the same electricity generation sector value of a comparable country:

1. Austria: Tide, wave, ocean - France.
2. Belgium: Tide, wave, ocean - France.
3. Bulgaria: Solar Photovoltaic - Romania; Tide, wave, ocean - France.
4. Cyprus: Solar thermal - Spain; Tide, wave, ocean - France.
5. Germany: Tide, wave, ocean - France; Geothermal - Austria.
6. Denmark: Tide, wave, ocean - France.
7. Estonia: Solar Photovoltaic - Sweden; Tide, wave, ocean - France.
8. Spain: Tide, wave, ocean - France; Geothermal - Portugal.
9. Finland: Tide, wave, ocean - France.
10. France: Solar thermal - Spain; Geothermal - Austria.
11. Greece: Tide, wave, ocean - France.
12. Croatia: Tide, wave, ocean - France; Solar thermal - Spain; Geothermal - Austria.
13. Hungary: Solar thermal - Spain; Solar Photovoltaic - Romania; Tide, wave, ocean - France.
14. Ireland: Solar Photovoltaic - United Kingdom; Geothermal - Austria.
15. Italy: Tide, wave, ocean - France.
16. Lithuania: Solar Photovoltaic - Sweden; Solar thermal - Spain; Geothermal - Austria; Tide, wave, ocean - France.
17. Luxembourg: Tide, wave, ocean - France.
18. Latvia: Solar Photovoltaic - Finland.
19. Malta: Hydro - Italy; Wind - Italy; Tide, wave, ocean - France.
20. Netherlands: Solar thermal - Spain; Tide, wave, ocean - France.
21. Poland: Solar Photovoltaic - Czech Republic; Tide, wave, ocean - France.
22. Portugal: Tide, wave, ocean - France.

23. Romania: Tide, wave, ocean - France; Solar thermal - Spain; Geothermal - Italy.
24. Sweden: Tide, wave, ocean - France; Solar thermal - Spain; Geothermal - Austria.
25. Slovenia: Wind - Italy; Solar Photovoltaic - Austria; Tide, wave, ocean - France.
26. Slovakia: Tide, wave, ocean - France; Geothermal - Italy.
27. United States: Tide, wave, ocean - Canada.
28. Japan: Tide, wave, ocean - France.
29. Canada: Geothermal - United States.
30. South Korea: Tide, wave, ocean - France; Solar thermal - China.
31. Brazil: Solar thermal - Spain; Tide, wave, ocean - France; Solar Photovoltaic - Mexico.
32. India: Tide, wave, ocean - France; Solar thermal - China; Geothermal - China.
33. Mexico: Tide, wave, ocean - France; Solar thermal - United States.
34. Russia: Solar thermal - Spain; Tide, wave, ocean - France; Solar Photovoltaic - Sweden.
35. Australia: Tide, wave, ocean - France; Geothermal - United States.
36. Turkey: Solar thermal - Spain; Solar Photovoltaic - Italy; Tide, wave, ocean - France.
37. Taiwan: Tide, wave, ocean - France; Solar thermal - China; Geothermal - China.
38. Norway: Tide, wave, ocean - France; Solar Photovoltaic - Sweden.
39. Indonesia: Wind - India; Tide, wave, ocean - France; Solar thermal - Spain; Solar Photovoltaic - India.
40. South Africa: Tide, wave, ocean - France; Solar thermal - Spain.
41. r.o. Africa: Tide, wave, ocean - France; Solar thermal - Spain.
42. r.o. Middle East: Tide, wave, ocean - France; Solar thermal - Spain.
43. r.o. Europe: Tide, wave, ocean - France; Solar thermal - Spain; Solar Photovoltaic - Romania.
44. r.o. Asia: Tide, wave, ocean - France; Solar thermal - China.
45. r.o. America: Tide, wave, ocean - France; Geothermal - Italy.

A.3 Calculating material footprint associated with capital investments

The CAPEX (in €/MW) is derived from projections specific to the European Union as reported in the 2014 Energy Technology Reference Indicator (ETRI) by Carlsson et al. [4]. We have utilized the projected CAPEX figures for the year 2020, considering it to be the most representative for current conditions. Notably, Carlsson et al. [4] differentiated between onshore and offshore wind installations; we have utilized their average CAPEX values for these technologies. Additionally, for electricity production technologies categorized as "not elsewhere classified (n.e.c.)" we have employed the average CAPEX across all other technologies.

Table S1: CAPEX for each electricity generation technology. Source: Carlsson et al. [4]

EXIOBASE 3.8 industry name	CAPEX 2020 (in 1,000 €/ MW)
Production of electricity by coal	1,600
Production of electricity by gas	700
Production of electricity by nuclear	4,350
Production of electricity by hydro	3,360
Production of electricity by wind	2,115
Production of electricity by petroleum and other oil derivatives	1,150
Production of electricity by biomass and waste	2,620
Production of electricity by solar PV	900
Production of electricity by solar thermal	4,500
Production of electricity by tide, wave, ocean	5,095
Production of electricity by geothermal	4,970
Production of electricity n.e.c.	2,850

The capacity factors for each country in EXIOBASE 3.6 are based on the capacity factors as published by Conti et al. [5]. Conti et al. [5] only provides one capacity factor for wind and solar. Moreover, the capacity factors for "Production of electricity by biomass and waste" and "Production of electricity by geothermal" were absent and therefore taken from the ETRI report by Carlsson et al. [4] and assumed to be equal for all regions.

Table S2: Capacity factor for each region. Source: Conti et al. [5] and Carlsson et al. [4]

Country	Coal	Gas	Nuclear	Hydro	Wind	Petroleum	Biomass	Solar PV	Solar Thermal	Tide Wave Ocean	Geothermal
United States	66	26	90	40	27	13	70	27	27	0	95
Canada	62	29	78	56	26	20	70	26	26	0	95
Mexico/Chile	64	51	73	37	23	40	70	23	23	0	95
Brazil	44	29	85	56	24	28	70	24	24	0	95
Other Americas	43	31	80	57	26	53	70	26	26	0	95
OECD Europe	51	39	77	40	18	19	70	18	18	0	95
Non-OECD Europe	41	43	77	34	14	10	70	14	14	0	95
Russia	38	52	80	40	3	66	70	3	3	0	95
China	54	19	83	37	18	18	70	18	18	0	95
India	60	50	59	34	18	35	70	18	18	0	95
Japan	62	44	48	40	15	26	70	15	15	0	95
South-Korea	82	40	88	25	16	43	70	16	16	0	95
Non-OECD Asia	62	42	88	38	22	34	70	22	22	0	95
Middle East	21	39	9	15	23	84	70	23	23	0	95
Africa	73	44	79	49	27	54	70	27	27	0	95
Australia/New Zealand	65	31		32	25	33	70	25	25	0	95

For deviding the capital investment (GFCF) for each electricity technology over EXIOBASE 3.8, we used the CAPEX breakdown of Černỳ et al. [6] which is based on the ETRI 2014 report [4]. As Černỳ et al. [6] distinguished between wind onshore and wind offshore, we used the average between the two categories in this work. Additionally, Černỳ et al. [6] distinguished Solar PV for residential and for utility scale, for which we also used the average between the two categories.

Table S3: Example of a concordance matrix matching the GFCF breakdown for each electricity generation technology with the EXIOBASE 3.8 industries for electricity from geothermal energy. For full concordance table see Supplementary Information of Černỳ et al. [6].

Component	EXIOBASE 3.8 industry name	Share (%)
	Geothermal	
Civil and structural costs	Construction (45)	5.0
Mechanical equipment supply and installation costs	Manufacture of machinery and equipment n.e.c. (29)	51.0
Electrical and I&C supply and installation	Manufacture of electrical machinery and apparatus n.e.c. (31)	7.0
Project indirect costs	Financial intermediation except insurance and pension funding (65)	4.0
	Activities auxiliary to financial intermediation (67)	4.0
	Computer and related activities (72)	4.0
	Other business activities (74)	4.0
Owner's costs	Construction (45)	5.3
	Insurance and pension funding except compulsory social security (66)	5.3
	Real estate activities (70)	5.3
	Computer and related activities (72)	5.3

B Supplementary Results

For all results the aggregation of countries into continents is based on Fig. 3.

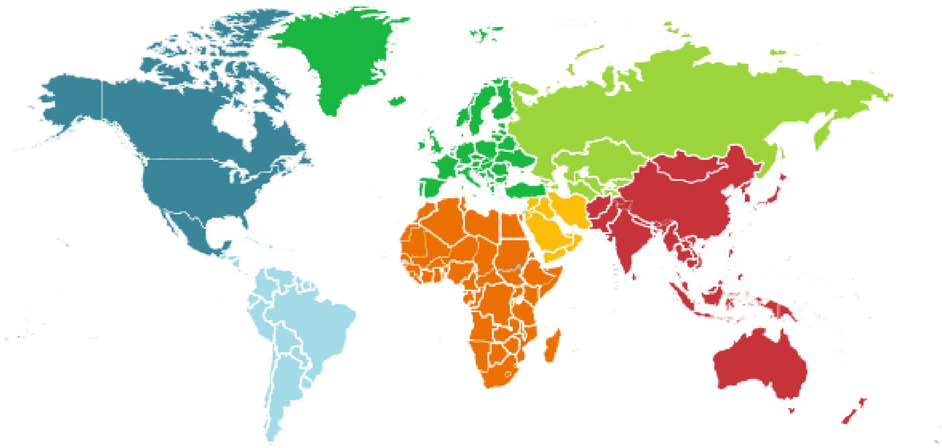

Figure S1: Continent aggregation as used in results Figure 2, 3 and 4.

Table S4: Yearly material extraction in kiloton

	Total extraction	2015		BAU		Fossil Fuel		100% Renewable	
	(2015)	Abs [2]	% [3]	Abs [2]	% [3]	Abs [2]	% [3]	Abs [2]	% [3]
Al	239,114	843	0.35	106	0.04	290	0.12	315	0.13
Cu[1]	1,674	10.4	0.62	1.0	0.06	2.8	0.16	4.1	0.24
Pb	70,588	350	0.50	26	0.04	48	0.07	41	0.06
Ni	370,760	2,561	0.69	182	0.05	387	0.10	381	0.10
ONM	230,418	1,048	0.45	116	0.05	276	0.12	389	0.17
PGM	30,560	98	0.32	17	0.06	71	0.23	126	0.41
Zn	246,007	1,509	0.61	160	0.07	358	0.15	290	0.12
FF[1]	11,072	484	4.37	40	0.36	71	0.64	17	0.15

- [1] in thousands
- [2] Absolute material extraction per year
- [3] Share of total annual global material extraction.

Table S5: Percentage increase of overall annual material footprint of 100% renewable scenario compared to fossil fuel scenario

Material	percentage increase
Aluminium	8.67
Copper	48.10
Lead	-15.33
Nickel	-1.53
ONM	40.78
PGM	78.10
Zinc	-18.90

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