Material requirements for future low-carbon electricity projections in Africa

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ABSTRACT

Deploying low-carbon electricity systems in developing countries is critical for meeting climate targets while increasing wellbeing. Direct emissions from operating electricity generation are well-understood, however, materials required to construct technologies and their emissions - embodied emissions - are frequently overlooked. This paper quantifies the material implications of proposed electricity systems in 47 African countries from 2015 to 2065, involving a reference scenario, and two Paris-Agreement scenarios (1.5 °C and 2.0 °C of warming). A purpose-built model, called Mat-dp (Material Demand Projections) is used for scenario assessment. Mat-dp integrates electricity generation projections with material requirements by technology, estimating material budgets, embodied emissions, and jobs. The resulting construction material mass grows 20-fold from 2015 to 2065, with the highest growth in the reference scenario. As low-carbon electricity capacity grows, embodied emissions from materials increase, reaching 47 MtCO2 in the 2.0 °C scenario by 2065. Three bulk materials, concrete, steel, and aluminium, make up 64-66% of the total materials required by 2065, and 59-61% of the total embodied emissions. The Paris Agreement scenarios show lower material demand, particularly bulk materials, but higher specialised material demand. Increasing low-carbon electricity generation while decarbonising industry offers a higher emission reduction potential compared to solely switching to low-carbon electricity. Estimated new jobs are 1.6 million per year, mostly from solar.

1. Introduction

Energy access can improve wellbeing and development [1]. However, energy use has environmental consequences. Namely, energy-related emissions (transport, buildings, industry) are estimated to contribute 73% to the total 50 Gt CO2-eq of global emissions [2]. Thus, a shift towards using low-carbon energy is essential to reduce emissions. Electricity is part of the energy sources experiencing this shift, with low-carbon electricity generation technologies ranging from renewables, to biomass, and to fossil-fuels with Carbon Capture and Storage (CCS). Electricity access is also tracked in different parts of the world, given its importance in providing specific services (i.e., what people need or want which is dependent on resource transformations), such as illuminations, sustenance, communication, among others. Despite recent progress in electricity access, the number of people without electricity access was estimated at 770 million in 2019 [3], with 75% of these living in Sub-Saharan Africa.

The IEA [4] warns that reaching a global carbon-neutral system by 2060 will require rapid deployment of clean energy technologies, thus avoiding locking in high-carbon systems, i.e., creating unavoidable emissions with a duration related to the systems in place. Yet, Tong et al. [5] analyse committed emissions from existing infrastructure and estimate that, of the total committed emissions (658 Gt CO2), 54% is anticipated to come from existing electricity plants, due to both their high lifetimes and their high share of total annual emissions. Alova et al. [6] further warn of high carbon lock-in risks for Africa, unless a rapid decarbonisation shock occurs leading to large-scale cancellation of the fossil fuel plants currently in the pipeline. Thus, if Africa and other developing regions are to avoid locking in high emissions, prompt action is required. However, several challenges to deploying low-carbon electricity systems exist, including technological uncertainty. For example, technological uncertainty persists for CCS technologies and their ability to scale to meet their future projections, leading to doubts that they will contribute to net zero emissions by 2050 [7].

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Abbreviations: AfCFTA, African Continental Free Trade Area; BECCS, Bioenergy with Carbon Capture and Storage; C&I, Construction and Installation; CCS, Carbon Capture and Storage; CSP, Concentrated Solar Power; EVA, Ethylene-vinyl acetate; GHG, Greenhouse gas; IEA, International Energy Agency; IO, Input Output; LCA, Life-cycle Analysis; Mat-dp, Material Demand Projections; MEFA, Material and Energy Flow Analysis; MENA, Middle-East and North Africa; MFA, Material Flow Analysis; PV, Photovoltaic; PVC, Polyvinyl chloride; PWR, Pressurised Water Reactor; SSA, Sub-Saharan Africa.

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This paper aims to compare the material implications of shifting electricity generation technologies based on projections in African countries. The shifts include additions of more renewable energy to the electricity mix to contribute to lowering global emissions. Reducing global emissions would lessen the forecasted climate impacts in the region, since seven African countries are already in the top ten most vulnerable countries in the world [8]. The study focuses on 47 African countries using the electricity projections and scenarios for the years 2015–2065 created by Pappis et al. [9]. The authors have published this in an academic format and further extended the scope of the model [10].

This paper addresses the full life-cycle of systems which provides more realistic and complete climate mitigation. This requires balancing the upfront investment of emissions required for constructing electricity systems—called embodied emissions—against the reductions in direct emissions from electricity generation to ascertain how quickly overall emissions can be reduced. This paper addresses the question: what are the material implications for delivering future electricity systems in African countries? The areas of focus surrounding the question include calculating material requirements, environmental impacts, and discussing their implications for future electricity demand and emissions. The results obtained may aid developing regions to identify opportunities to avoid locking-in emissions in their electricity systems.

2. Literature review

2.1. Resource use in electricity systems and its consequences

Switching to low-carbon electricity has consequences for the resources used, the resulting emissions, and the electricity grid infrastructure. Deetman et al. [11] explain that the material demand of global electricity systems has been growing rapidly as a result of the shift from (fossil-)fuel-intensive technologies to material-intensive renewable technologies, and increased demand. Further, higher shares of renewable electricity will require electricity storage and grid expansion to guarantee reliable and affordable electricity supply [11]. Highlighting specific materials, Kalt et al. [12] acknowledgments that, historically, electricity infrastructures represent a high share of global copper and aluminium stocks, but are less important for the global production of iron/steel and concrete. The studies by Deetman et al. [11], Kalt et al. [12] and Kalt et al. [13] are part of the few studies that focus on the material implications (e.g., impacts across the entire life cycle of a technology) that accompany changes to electricity systems [14]. Yet, these studies are conducted at a global or regional level, making them less relevant to decision-makers in specific countries.

Demand for critical materials for electricity generation and other electricity-related uses has increased in recent years, alongside demand for traditional bulk materials such as steel and cement. Critical materials include copper, lithium, nickel, cobalt, and rare earth elements used in applications such as wind turbine magnets or car batteries. The IEA [15] estimates that the increase in renewable electricity generation has led to a 50% increase in the average amount of minerals for each new unit of electricity generation capacity since 2010. Deetman et al. [16] estimate that the demand for critical materials in the electricity system is expected to grow, with neodymium growing from 3 to 4.4-fold and copper over two-fold between 2015 and 2050 based on a 2.0 °C scenario [11]. These estimates of the critical material impacts of electricity technologies have not yet been applied at country level, to inform local energy planning and decision making.

The increasing use of resources, particularly fossil-based energy, has led to unprecedented levels of greenhouse gas (GHG) emissions accumulated in the atmosphere, which drive climate change. In response, countries have set themselves commitments to limit GHG emissions in international agreements, such as the Paris Agreement [17]. However, meeting these targets requires vast changes to energy and production systems and significant investment in new infrastructure, which in turn drives demand for new materials and manufactured goods and additional embodied emissions. The IEA [18] estimates that already 40% of global emissions can be attributed to industry (including upstream electricity and heat emissions). Additional demand for new energy system infrastructures, will make the decarbonisation of industry even more challenging.

Studying renewable energy technologies with their life cycle implications, Hertwich et al. [19] conclude that deploying low-carbon electricity generation technologies can lead to lower environmental impacts to air and water while supplying more electricity. Hertwich et al. [19] confirm that as renewables are taken up, material requirements increase, e.g., copper for PV systems and iron for wind power, yet the pollution from the higher material requirements is small compared to fossil-fuel direct emissions. Hertwich et al. [19] estimate that for every kWh of electricity produced using renewable sources, 0.1–0.25 kWh of non-renewable sources are currently required, highlighting the need to adapt material production to use less energy and emit less emissions. This follows a more general trend, observed by Scott et al. [20], where material efficiency strategies (related to embodied emissions) are overshadowed by energy efficiency strategies (related to direct emissions) in the policy initiatives of the European Union, missing out on opportunities to further reduce total emissions.

In addition to the increased material demand, emissions and costs, the transformation to low-carbon electricity generation requires considerations of the land area needs [21] or employment opportunities created [22]. Comparing key renewable and fossil-fuel electricity generation, Chatzimouratidis et al. [21] estimate that the highest land requirements are for biomass (5000 km²/1000 MW), while the lowest are for fossil-fuel electricity plants and nuclear (estimating 2.5 km²/1000 MW for all these types). Ram et al. [22] explore global employment changes resulting from a move to 100% renewable sources by 2050 and conclude that the total employment in the electricity sector increases from 21 million in 2015 to nearly 35 million in 2050, highlighting an important co-benefit of low-carbon electricity. Ram et al. [22] identify solar PV, batteries and wind power as the major job-creating technologies.

2.2. Techniques to study material use and their environmental implications

The material requirements and environmental implications of electricity technologies can be studied with different tools. Among them, Life-cycle Analysis (LCA) [19] involves defining the system to study and calculating its environmental impacts. LCA begins by accounting materials, but results focus on the environmental implications of a given system.

LCA can be used to study electricity generation technologies, obtaining measures of life-cycle emissions over the annual electricity generation in the lifetime of a given technology. In many cases, either LCAs are completed for specific technologies (e.g., oil-fired steam turbine in Singapore [23], or reviews are carried out to compare several individual studies [24,25]). Amponsah et al. [25] showed that the lowest total GHG emissions are associated with offshore wind (with 5.3–13 kgCO₂eq/MWh), while waste and dedicated biomass technologies presented higher emissions (97.2–1000 and 14.4–650 kgCO₂eq/MWh respectively) due to the emissions generated in the production or treatment of the biomass or waste fuels. Amponsah et al. [25] also concluded that the variability across the different energy technology LCA studies is wide, given differences in emissions, study assumptions and modelling choices. Addressing this variability, some studies have performed comparable LCAs of different electricity generation technologies by finding common assumptions and data sources. LCA can also be used for country-level studies, whose advantage is to provide a credible evaluation of government policy. Europe, Asia and North America are the most studied regions for electricity LCAs [26], with only a handful of examples available in the literature on developing and emerging countries (e.g., Mexico [27] or Nigeria, Ghana, and Ivory Coast).
The study of material stocks, their transformations and use has been the subject of other theoretical frameworks and quantification studies. The theoretical frameworks include the socio-economic metabolism [29–31] and one of its branches known as the “stock-flow-service nexus” [12]. These link biophysical resources that lead to service provision and well-being. The quantification of material stocks and flows include techniques such as Material Flow Analysis (MFA), its inclusion of energy as Material and Energy Flow Flow Analysis (MEFA) [32,33], MFA including material stocks and flows in what is known as Dynamic MFA [34], or Input-output (IO) analysis [35]. Each of these techniques define system boundaries differently and calculate material use either with country data or predefined information about material use in different products. The techniques of MFA and MEFA focus solely on material requirements, with stocks sometimes being incorporated (e.g. Refs. [34,36],[37]). IO may also include monetary flows or Physical-IO tables [38], with the limitation that the translation of monetary flows into physical ones is subject to data quality and interpretation of the monetary flows.

To bring material quantification techniques together and gather useful insights, one option is to use an integrated LCA methodology assessing technologies in a comparable way [19], while another option is to combine LCA and MFA techniques, as demonstrated by Kalt et al. [12]. LCA can provide material requirements of different energy technologies, while MFA can aggregate such material requirements to obtain country or regional-level material requirements for stocks and flows. Despite the novelty presented by Kalt et al. [12], gaps still exist in using LCA data of energy technologies to assess scenarios according to country plans, as well as estimating industrial requirements for building the proposed electricity systems.

The research presented in this paper is organised as follows: Section 2 presents the LCA data included in this study and the methods used to analyse it. Section 3 presents the modelling results. Section 4 discusses the results and compares them with current literature. Finally, section 5 shows the conclusions from the paper.

3. Data and methods

MatG-dp (Material Demand Projections) is a model created for the purpose of studying the material implications of changing electricity systems. The model can be used to study a single country and their electricity projections and can also be scaled up to compare different countries, regions, and years.

Mat-dp draws information from several LCA analyses to estimate the material requirements of different electricity technologies in a consistent manner. The LCA studies provide the material requirements of different energy technologies, while MFA techniques influence the aim of Mat-dp to aggregating materials to obtain country or regional-level material requirements. This method is designed to provide consistency across LCA scopes and energy technologies.

The different energy technologies considered by the LCA analyses included in Mat-dp are Solar, Wind, Hydro, Biomass, Geothermal, Nuclear, Gas, Oil, Coal, and Gas with CCS. The LCA studies used in Mat-dp are limited to those that gather material requirements per energy technology in units of mass only. The system boundaries used for the study include the material requirements of electricity generation power plants including some fuel cycle materials related to nuclear only. Thus, neither transmission and distribution, electricity storage nor fossil fuel extraction and refining are included. The LCA data can be used to estimate the total materials used, and the embodied and direct emissions of each technology. The LCA data is normalised for the mass of materials for a unit of electricity output (e.g., in kg/MWh) in the lifetime of each technology. Scenarios of electricity generation can then use the normalised technologies to calculate materials used for a given electricity system that combines several generation technologies and their environmental implications. The environmental implications that may be calculated with Mat-dp include embodied emissions, water use, material costs, and material recycling rates. Additionally, employment information for each energy technology is gathered and used to calculate the number of jobs for each technology.

In this study, Mat-dp is applied to electricity generation scenarios of 47 African countries only. The scenarios include a reference case and two scenarios related to the Paris Agreement. Additional information on the scenarios is given in Section 3.3. To the best of our knowledge, this is the first time that a method to estimate material requirements and their implications drawing from LCA studies is applied to detailed African country electricity scenarios, thus enabling informed decisions to be made. Details of the data and methods used are explained in the following sections.

3.1. Energy technology LCA data

Table 1 shows the average factors and characteristics of the plants considered in the LCA studies gathered, which were used to normalise the materials and electricity output per lifetime of each technology.

Table 2 shows the materials needed per electricity output of each energy technology. It can be observed that critical materials (e.g., carbon fibre, ceramics, silicon) add up to less than 2% of the total material mass across all technologies. However, these critical materials can lead to resource constraints in countries with critical material scarcity or lack of knowledge on certain production processes.

3.2. Material requirements and embodied emissions of energy technologies

Table 3 presents the materials included in the study and their CO₂ emissions footprint. The materials included are those related to the construction of each type of power plant, but not the fuel used, if applicable. This is because fuel use is associated to direct emissions from burning, whereas the focus of the study is embodied emissions from construction materials. The materials with the highest embodied emissions per mass of material are carbon fibre (20.30 kgCO₂/kg material) and aluminium (12.58 kgCO₂/kg material).

Additional environmental implications considered in Mat-dp are the water use, costs, and recycling rate. These factors are also taken from Refs. [61,62]. Further details on them can be found in the Supporting Information (SI).

3.3. African electricity generation scenarios

In this paper, Mat-dp is used to compare the environmental impacts related to the materials used in electricity generation using scenarios for the 47 African countries (shown in Table 4). Pappis et al. [9] consider three scenarios for every country: a reference scenario, which includes “the national energy policies that were in place until 2017”, and the 1.5 °C and 2.0 °C scenarios, which align emissions with the agreed climate targets under the United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement. The scenarios forecast that a 10-fold increase in electricity generation capacity will be required from 2015 to 2065 to meet the growing electricity demand. Such increase in electricity generation requires low-carbon technologies to avoid the worsening of the expected climate effects. Then, the 1.5 °C and 2.0 °C scenarios propose an increase in renewable energy sources, facilitated by their falling costs, and an increase in nuclear power plants and Carbon Capture and Storage (CCS) combined with biomass and fossil fuels. Such plans aim to decrease the reliance on coal for electricity. The scenarios include the electricity output and the cumulative and new capacity of each type of electricity plant. The scenarios are used in this paper to calculate the material implications of the proposed systems divided by region, type of materials and type of generation technologies for each year.

Fig. 1 shows the aggregate installed capacity (above), the aggregate
3.4. Calculating materials required and environmental implications

Details of Mat-dp are further explained in the following sections, including the calculations made specifically for the 47 African countries.

The first step is to determine the mass of each material $i$ per electricity output of each technology $j$, $m_{ij}$, which is achieved by dividing the normalised mass of material $m_i$ for each technology $j$ by the electricity output, $EO_j$, over the lifetime of such technology, in kWh. These quantities will be referred to as being normalised, since they allow the electricity output, $EO_j$, for each technology $j$ to be calculated.

Equation (1) shows the calculation of the electricity output over a lifetime of a technology, $EO_j$, considering the capacity of the technology, load factor and average lifetime.

$$EO_j = m_{ij} \cdot L$$

Equation (1).
Table 4

| Material     | Average CO₂ footprint [kgCO₂/kgmaterial] |
|--------------|-------------------------------------|
| Aluminium    | 12.58                               |
| Bentonite    | 0.03                                |
| Carbon Fiber | 20.3                                |
| Cast Iron    | 2.20                                |
| Cement       | 0.87                                |
| Ceramics     | 1.55                                |
| Concrete     | 0.10                                |
| Copper       | 3.63                                |
| Epoxy        | 7.19                                |
| EVA          | 2.11                                |
| Fibre Glass  | 2.30                                |
| Glass        | 0.79                                |
| Lubricant    | 1.07                                |
| Non-Ferrous Metal | 8.63                      |
| Paint        | 2.42                                |
| Plastic      | 2.72                                |
| PVC          | 2.50                                |
| Resin        | 3.63                                |
| Sand         | 0.02                                |
| Silicon      | 5.34                                |
| Steel        | 2.46                                |
| Stainless Steel | 5.67                        |
| Zircon       | 0.92                                |

Table 4: African regions and countries included in this study.

| Region         | Countries and ISO code |
|----------------|------------------------|
| Central        | Cameroon (CM), Central African Rep. (CF), Chad (TD), Congo (CG), Democratic Rep. of Congo (CD), Equatorial Guinea (GQ), Gabon (GA) |
| Eastern        | Burundi (BI), Djibouti (DjJ), Eritrea (ER), Ethiopia (ET), Kenya (KE), Rwanda (RW), Somalia (SO), Sudan (SD), Tanzania (TZ), Uganda (UG) |
| Northern       | Algeria (DA), Egypt (EG), Libya (LY), Mauritania (MR), Morocco (MA), Tunisia (TN) |
| Southern       | Angola (AO), Botswana (BW), Lesotho (LS), Malawi (MW), Mozambique (MZ), Namibia (NA), South Africa (ZA), Swaziland (SZ), Zambia (ZM), Zimbabwe (ZW) |
| Western        | Benin (BJ), Burkina Faso (BF), Cote d’Ivoire (CI), Gambia (GM), Ghana (GH), Guinea (GN), Guinea Bissau (GW), Liberia (LR), Mali (ML), Niger (NE), Nigeria (NG), Senegal (SN), Sierra Leone (SL), Togo (TG) |

Where \( C \) is the plant capacity, i.e., the maximum electricity output under ideal conditions in W; \( f \) is the load factor, i.e. the ratio of actual electricity output over a given time period to the maximum possible output over the same period; \( L \) is the planning lifetime in years; and 8.76 is the conversion factor to go from W-year to kWh.

The environmental impacts, i.e. the water use, costs and recycling rates, are first calculated as the normalised impacts per electricity output (in kWh) for every technology. These can then be used to calculate the country-specific impacts per technology. Equation (2) then shows how to calculate country-specific impacts of the 47 African countries considered using the projected electricity output per technology and the normalised impacts. These can be then grouped by region or type of generation technologies for each year.

\[
I = \sum_{i=1}^{N} \left( \frac{EO_{j}}{EO_{i \text{ over lifetime}}} \frac{m_{i}}{m_{j}} \right) I_{\text{measure}}\tag{2}
\]

Equation (2).

Where \( I \) refers to the environmental impacts of the country in question whose units can be gCO₂, Lwater, € or $material for the impacts of emissions, water use, costs and recycling rate respectively. \( EO_{j} \) is the projected electricity output of technology \( j \) used in the country (i.e., the country projection). \( EO_{i \text{ over lifetime}} \) is the electricity output over the lifetime (in kWh) of the same technology \( j \), and \( \frac{m_{i}}{m_{j}} \) refers to the environmental impacts per mass of a given material \( i \). The last two fractions of the equation are the normalised environmental impacts. The impacts of every material (\( i \) to \( N \)) used in all the technologies (\( j \) to \( M \)) in a country mix are summed to obtain the total impact.

3.5. Calculating number of jobs

Several methods exist to calculate the job creation for energy technologies, using bottom-up and top-down techniques. Bottom-up relies on detailed job requirements per technology type that are then generalised, while top-down techniques use input-output models using different regional multipliers. In this paper, the number of jobs for each energy technology were calculated based on Ram et al. [22], who consider yearly and regional multipliers, as well as job types. Ram et al. [22] split the job types by manufacturing, construction and installation, operation and maintenance, fuel supply, and decommissioning. Then, the jobs considered were only those related to local manufacturing, and construction and installation (C&I), since those are the ones associated to local material production instead of electricity plant operation and are thus related to embodied emissions. Equation (3) and Equation (4) show the calculation of manufacturing and C&I respectively. Further details on how the method of Ram et al. [22] was adapted for Mat-dp is shown in the SI.

Manufacturing (local) jobs = \( 1000 x y (1 - z) a \) \tag{3}

Equation 3

Construction and installation jobs = \( 1000 x y (1 - z) a \) \tag{4}

Equation (4). Where \( x \) refers to new installed capacity (GW), \( y \) refers to the employment factor (depending on the job type), \( z \) refers to the Capex decline factor, and \( a \) refers to the regional factor.

4. Results

The results are presented as the normalised total emissions for the technologies included in Mat-dp, followed by the detailed results for African countries. Such results include material mass and embodied emissions from materials for the different scenarios, split by region and country, and the yearly employment split by job type and technology.

4.1. Embodied and direct emissions by technology

Fig. 2 shows the embodied emissions per electricity output over the lifetime of the technology and the total use-phase (or direct) emissions per electricity output for the normalised technologies included in Mat-dp. Direct emissions per electricity output are higher for fossil-fuel technologies than for renewable ones. Embodied emissions of renewable technologies account for most of the total emissions, and, in contrast, use-phase emissions of fossil-fuel technologies are predominant, even in the cases where CCS is considered. Use-phase emissions of fossil fuels are 10–30 times higher than embodied emissions of renewable technologies. Use-phase emissions are higher for fossil fuels, given the combustion process which releases CO₂. The embodied emissions of onshore wind result higher than offshore, mainly due to the concrete foundations required in onshore wind installations. These results complement observations by Deetman et al. [11] and Kalt et al. [12] regarding the high material intensity of renewable energy technologies and low embodied emissions of fossil-fuel technologies.

4.2. Mat-dp results for African countries

4.2.1. Mass of materials required

Fig. 3 shows the total mass of materials for the given set of electricity generation technologies used each year in each scenario, with the top
Fig. 1. Aggregate installed capacity (above), aggregate power generation (middle) and new electricity generation capacity (bottom) for different electricity generation scenarios in Africa between 2015 and 2065.
graph stacking each material to show the proportion of the total, and the bottom graph showing the trends of the heaviest materials. The 10-fold electricity generation capacity increase between 2015 and 2065 results in a 20-fold (18.7–20.9) increase of the mass of materials, e.g., from 2.8 Mt to 58 Mt in the reference scenario. The reference scenario is the one with the highest material requirements, while the Paris Agreement scenarios have similar total mass requirements. In all scenarios, the highest mass of materials required is concrete, which triples in the reference scenario between 2040 and 2065. Concrete is also the material with the highest mass in the other two scenarios, but the total mass is around 4 Mt lower than for the reference scenario by 2065.

The growing use of coal power plants in the reference scenario is replaced by gas, nuclear, hydro, solar CSP, and small amounts of wind and gas CCS in the Paris Agreement scenarios. Concrete, sand, steel, and PVC are the materials with the highest amounts required in the technologies of the Paris Agreement scenarios, with concrete having an order of magnitude more than the others. However, the amounts of specialised materials required in the Paris Agreement scenarios are higher than the reference one, with materials such as bentonite, fibre glass or resin requiring an order of magnitude more materials.

4.2.2. Embodied emissions

Fig. 4 shows the total embodied emissions in each scenario for the given set of electricity generation technologies used each year split by material, with the top graph stacking each material to show the proportion of the total, and the bottom graph showing the trends of the highest-emitting materials. These emissions are 7% higher in the 2.0 °C scenario, reaching 47 Mt CO₂ by 2065, compared to the reference scenario, reaching 44 Mt CO₂ by 2065. The reference scenario shows a more linear increase of aluminium emissions than the other two scenarios, while the 2.0 °C has higher emissions of steel and stainless steel than the other scenarios. The two materials with the highest total embodied emissions are steel and aluminium. Embodied emissions to suit the required steel demand reach 14.6 Mt CO₂ in the 2.0 °C scenario by 2065, and 12.9 Mt CO₂ in the reference scenario. Thus, for steel, the Paris agreement scenarios require 1.2–1.7 Mt CO₂ more than the reference scenario. Aluminium, one of the materials with the highest embodied emissions intensity, has cumulative emissions that are between 11.7 and 12.0 Mt CO₂ by 2065 in all scenarios. The embodied emissions of stainless steel in the 2.0 °C scenario are 5.2 Mt CO₂ while the other scenarios have similar values of 3.3–3.4 Mt CO₂, which is due to the increase in Solar CSP generation in the 2.0 °C scenario.

The 7% higher embodied emissions in the Paris Agreement scenarios compared to the reference scenario suggest that shifting to renewable technologies may bring an increase in embodied emissions from materials. Thus, to attain the highest total emission savings and provide the specialised materials needed, a joined-up strategy may be designed where, as renewables are added to the electricity mix of countries, strategies to decrease embodied emissions and increase industrial capacity are created.

Fig. 5 shows the total embodied emissions for the given set of electricity generation technologies used each year for the three African electricity generation scenarios split by region. Most regions are expected to reach similar embodied emissions in the 2.0 °C scenario by 2065: Northern (11.4 Mt CO₂), Southern (11.2 Mt CO₂), Eastern (10.0 Mt CO₂) and Western Africa (9.7 Mt CO₂). Central Africa is the region where emissions are expected to increase later than all other regions, reaching only 5.0 Mt CO₂ by 2065 in the 2.0 °C scenario. In Central and Eastern Africa, the embodied emissions of the 1.5 °C scenario are 0.5–1.0 Mt CO₂ higher than the others, while in all other regions, the 2.0 °C scenario has the highest embodied emissions by 2065. This reflects that Central African countries are expected to have high emissions related to hydropower (reaching 3.7 and 3.3 Mt CO₂ in the 1.5 °C and 2.0 °C scenarios respectively by 2065) and solar PV (1.3 and 1.2 Mt CO₂ in the 1.5 °C and 2.0 °C scenarios respectively by 2065), while Eastern African emissions are associated to solar PV (7.2 and 6.7 Mt CO₂ for the 1.5 °C and 2.0 °C scenarios respectively).

Fig. 6 shows the cumulative embodied emissions by country between 2015 and 2065. In the 1.5 and 2.0 °C scenarios, the embodied emissions of Nigeria (NG, 4.8 and 6.4 Mt CO₂ in the 1.5 °C and 2.0 °C scenarios respectively in 2065) and South Africa (ZA, 3.1 and 3.8 Mt CO₂ in the 1.5 °C and 2.0 °C scenarios respectively in 2065) are higher than in the Reference scenario (NG: 4.1, ZA: 2.2 Mt CO₂ in 2065), being the highest in the 2.0 °C. In Nigeria the increase in the 2.0 °C scenario is due to the inclusion of emissions related to solar CSP materials, while in South Africa, the increase is due to higher wind material emissions.

The emissions reflect the materials required to transition away from fossil fuels and increases in capacity. In Nigeria, the emissions are related to natural gas in the Reference scenario being expected to reach 60 GW of installed capacity in 2065, and in the 2.0 °C, natural gas reaches 55 GW, while coal and oil decrease as nuclear energy increases up to 66 GW and the capacity of solar technologies is increased by 2065 [9], leading to additional material supply for such a transition. In turn, South Africa is expected to keep its reliance on coal, given the region’s reserves, while ramping up the capacity of solar PV from 2025 in the Reference scenario, while in the 2.0 °C scenario, a higher overall installed capacity is expected with the integration of more renewables, coal phase-out and biomass CCS technologies [9]. In contrast, countries like Mozambique (MZ) or Sudan (SD) have higher embodied emissions in the 1.5 °C, compared to the other two scenarios. This is related to the increase in renewables, e.g., solar, wind and hydropower [9].

The countries whose emissions are projected to grow the most are Nigeria (NG), South Africa (ZA), Egypt (EG), Ethiopia (ET), the Democratic Republic of Congo (CD), Sudan (SD) and Mozambique (MZ), whose order depends on the scenario. In each region, a handful of countries are responsible for over 50% of electricity demand and embodied emissions, also having the highest increases in them. The Western African demand and embodied emissions are driven by Nigeria; in the East, they are driven by Ethiopia, Sudan, Tanzania (TZ) and Kenya (KE); in the North by Egypt; and in the South by South Africa; and in the Central by the Democratic Republic of Congo.

4.2.3. Employment

The new jobs created based on the new installed capacity are shown in Fig. 7, which shows the specific types of jobs, and Fig. 8, which shows the jobs by technology. Generally, Africa would experience a growth mainly in construction and installation jobs and about half as many manufacturing jobs. The proportion of new jobs created are mainly due to solar PV, which ramp up after 2025, followed by coal in the reference
scenario, while coal jobs are replaced by wind and nuclear in the 1.5 °C and 2.0 °C scenarios. These findings are in line with the observation by Ram et al. [22] for Sub-Saharan Africa (SSA) and the Middle-East and North Africa (MENA) region that solar PV is the prime job creator. On average, 1.6 million jobs will be created every year to cope with the increased electricity generation, from around 0.5 to over 3 million jobs in a given year. Further, additional jobs will be created in the operation and maintenance of these electricity plants, although these were not in scope of this paper. Further, before 2025, around one million jobs due to hydropower are expected. There is a peril then if the skills required for such jobs are not transferable to the subsequent demand of jobs for solar PV. Strategies to manage such skill transferability are then required.

5. Discussion

5.1. Strategy for an effective switch to renewable energy technologies

The high direct emissions of fossil fuel technologies suggest that, as electricity capacity is built, switching to renewable technologies is a key first step that African countries can take to reduce total emissions from electricity systems. In turn, the high embodied emissions from renewable power plants imply that, for a decarbonisation strategy to have the highest benefits, reducing material emissions are required in parallel to renewable technology additions to electricity systems. This remains so even when accounting for emissions using system boundaries which include fuel cycles, transmission, distribution and storage, since the materials required for systems will shift away from fuel cycles except for nuclear energy. The specialised materials required for the low-carbon transition also suggest that planning in the areas of industrial capacity
5.2. Material impacts

In African electricity power plants, concrete, steel, and aluminium are three materials that present big opportunities to introduce material efficiency techniques, since they are projected to have either the highest mass (concrete, which reaches 27 to 31 Mt by 2065, depending on the scenario) or embodied emissions by 2065 (steel and aluminium, reaching 12.9–14.6 and 11.4–12.0 Mt CO\textsubscript{2} respectively, depending on the scenario). These materials were projected to have the highest amounts in the reference scenario; however, their embodied emissions were higher in the 2.0 °C scenario. Adding uncertainty to these values is considered in the future work section, however these African materials with the highest mass requirements obtained with Mat-dp, were also observed by Deetman et al. [11] who focused on global electricity systems by 2050. Deetman et al. [11] also included transmission and distribution materials, finding that the mass of aluminium required is also among the highest. Aluminium is used for substations and steel for mainly for transformers, and for electricity storage in small amounts. The high concrete demand is largely associated to hydropower, in line with a similar observation by Kalt et al. [12], who also identify that other electricity generation plants account for over half of the global demand for iron and steel stocks.

As renewables are taken up in African electricity systems, the increase in the use of specialised materials highlights the need to make

![Fig. 4. Embodied emissions for the given set of electricity generation technologies used each year and scenarios in Africa between 2015 and 2065 shown as total by stacking materials (top) and for the highest-emitting materials (bottom).](image-url)
plans for their increased production or trade-in countries that do not produce such materials. Some of these materials identified in this study are bentonite, fibre glass or resin, which require an order of magnitude more materials in the Paris Agreement scenarios.

5.3. Strategies to reduce material emissions and policy recommendations

The total African emissions were estimated to be 1185 Mt CO$_2$ in 2017, which corresponds to 4% of global emissions [67]. Cumulative

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Fig. 5. Total embodied emissions for the given set of electricity generation technologies used each year by scenarios and African regions between 2015 and 2065.

Fig. 6. Cumulative embodied emissions by decade for different electricity generation scenarios in African countries between 2015 and 2065. Refer to Table 4 for the country abbreviations.
Fig. 7. Total number of new jobs by job type for different scenarios in Africa between 2015 and 2065.

Fig. 8. Total number of new jobs for different electricity generation technologies and scenarios in Africa between 2015 and 2065.
embodied emissions for electricity in 2017 accounted for less than 1% of those emissions, however, assuming total emissions remain similar, by 2065 embodied emissions will account for less than 5% of the total in 2017. Although this fraction is low because it only represents emissions for electricity power plants, considering material provision has strategic importance since material production and use influence systems beyond electricity generation, e.g., materials for other systems and waste.

The increased material demand in African countries means that any country where the materials are produced-be it in Africa or abroad-to provide the required amounts may have room for improving industrial performance, depending on their existing performance. If the materials were to come from African production or abroad from nascent or inefficient industries, several strategies and policy changes to reduce material emissions could be implemented. These should aim to limit industrial emissions in parallel to the construction of electricity and other systems. The effect of reducing material emissions in electricity can spill over to the sectors of buildings, transport, commercial and others, since all these sectors require materials with the highest emissions, e.g., steel used in cars.

Three strategies are proposed to reduce material emissions mainly considering African industries: prioritising industrial decarbonisation, implementing material efficiency, and increasing regional and international cooperation. They are discussed below:

1. Prioritising industrial decarbonisation

Infrastructure building requires materials made by different industries. Then, there is a loop where, if industrial emissions are reduced before most of the infrastructure is created, emission savings can be achieved. Since emissions tend to be locked-into infrastructure for decades, this approach ensures that locked-in emissions are as low as possible. Examples are roads, bridges, or buildings, which use materials such as steel or concrete that can be produced with lower emissions.

In Africa, those industries with the largest capacity are good candidates for initiating emission reductions in their processes. For example, the largest African cement producers are located in the north, with Egypt (81 Mt of hydraulic cement in 2018) being the largest, followed by Algeria (27 kt) and Morocco (15 kt). In other regions, Nigeria (21 kt) and South Africa (15 kt) are the largest producers [68]. These producers are then key to deliver Africa’s strategies to reduce cement emissions by monitoring their performance and including it in local policies.

2. Implementing material efficiency in emission-intensive industries

Implementing material efficiency strategies may contribute up to 30% of the combined emissions reduction for concrete, steel, and aluminium globally in 2060 [69]. African industries may then have similar emission reduction opportunities, which should be further evaluated.

Emission reductions strategies have already been identified in the literature for emission-intensive materials. For steel, energy efficiency improvements can be achieved by improving operational efficiency and process yields, with the [70] encouraging steelmakers to achieve operational improvements similar to the top 15% performers. Further, the IEA [71] estimates that material efficiency can lead to reducing 40% of cumulative emissions. Wang et al. [72] advise that material efficiency measures must be combined with the adoption of low-carbon production technologies. The use of scrap steel for steel production is also advised, as it requires lower energy consumption and emissions compared to ore-based primary steel production. Yet, scrap must be carefully collected, so the resulting steel has the desired high quality. Wang et al. [72] predict that global scrap supply will rise around 3.5-fold from 2020 to 2050, with regions such as Europe, developed Asia and North America generating scrap equivalent to their steel demand by 2050. Africa is not included in such global projections, but this study is trying to raise awareness of the material demand in African nations so similar emission reduction strategies are quantified.

Several improvements have been identified for aluminium production. Haraldsson [73] highlight opportunities for the energy-demanding electrolysis, but also point at efficiency opportunities in the secondary aluminium production. Primary production is around ten times more energy-intensive than secondary production. Thus, material efficiency strategies can help maximise scrap collection to increase secondary production and reduce the total amount of aluminium used [74]. Specific strategies can be reducing scrap generation during manufacturing, reusing old scrap, and designing recyclable products. Decarbonising the power sources for aluminium production is also necessary, given its high electricity consumption. The IEA [74] estimates that Africa relies on purchasing electricity for aluminium production, whereas other parts of the world self-generate fully or partially.

3. Increasing regional and international cooperation

Many African countries are expected to build more infrastructure by 2065, which will increase the demand for materials. Then, regional studies on material demand may highlight opportunities for creating material pools. Material pools could have a similar style to the already existing power pools and COVID-19 vaccine manufacturing hubs, with manufacturing of key components being strategically organised depending on country resources and capabilities, balancing investment and enabling regional trade. Material pools would ensure that the required industries for building infrastructure have enough capacity, and that their performance is monitored, thereby increasing both regional economic development and emissions reduction potential.

Material trade in countries with less strong agreements can also be aided by the recent establishment of the African Continental Free Trade Area (AfCFTA) [75], with some of the materials needed for electricity systems being already identified as having export potential, e.g., steel, plastics, or copper.

Cooperation within Africa and abroad on material trade will be essential. The trade barriers such as tariffs or technical barriers that material exports within Africa face [75] should be considered in the AfCFTA and suggested regional material pools. The creation of material pools and other strategies discussed will also require international cooperation, as highlighted by the African Development Bank [8] who warns that reaching 77% of emission reduction commitments made by 2030 is conditional on receiving international support.

5.4. Country implications and risks

One the countries where emissions are projected to grow the most is Nigeria, which is also on the list of the ten most-threatened countries by climate change [8]. Six other African countries (Central African Republic, Chad, Eritrea, Ethiopia, Sierra Leone, and South Sudan) are also part of this list. Further, six countries accounted for 80% of the total emissions in Africa in 2017, which are South Africa, Egypt, Algeria (DZ), Nigeria, Morocco (MA), Libya (LY) [67]. Thus, if the switch to renewable electricity generation and emission reduction strategies discussed earlier are adopted regionally and globally, they have the potential to benefit the most vulnerable countries.

Climate change risks exist that will directly affect electricity generation in Africa. For instance, hydropower generation has the potential to decrease as reservoirs evaporate as a result of the long-term changes in the mean annual temperature of Africa [76]. Generally, most of Africa will experience droughts [77], while east Africa increases its water inter-annual variability [78], complicating forecasts and water management. These risks need to be considered to implement reliable electricity generation and material efficiency strategies, since it will be costly-both from an economic, but also from an embodied emissions perspective to make alterations to the systems.
5.5. Employment implications

The changing electricity system has consequences for the African workforce. African countries need to be prepared to satisfy the expected demand for new jobs by encouraging training or educational programmes and doing regional planning depending on the areas where the electricity generation technologies will be installed. This will be especially true if scenarios such as the 1.5°C is followed, where highly skilled jobs for nuclear power are required from 2045 onward. The labour intensity to make the employment calculations has been forecasted to be high in SSA in the earlier years (7.49 in 2015) and decrease in later years (e.g., 4.09 in 2050). In turn, in the MENA region, the labour intensity is forecasted to be lower, between 2.26 and 1.23 in the same period. These forecasts will need to be revised, as measures are taken to address labour, mainly in SSA.

5.6. Limitations of the study

The main limitations of this study can be split into two categories, those related to the underlying model assumptions and those related to the model application.

The limitations related to assumptions for Mat-dp include the system boundaries, the generic plant characteristics, the technologies considered, and the emission intensities. The system boundaries drawn for the electricity systems referred mainly to power plants but not fuel extraction, refining processing or transportation. The only technology which included some of those fuel cycles was nuclear. These boundaries were done that way since the materials used in fossil-based fuel cycles are hardly included in LCA studies - only their energy use tends to be included, which were the basis for this study. No transmission and distribution or storage was included either. The lack of material accounts for fuel cycles may result in lower embodied emissions of fossil fuel technologies, given that a broader system from fuel cycles to the power plants would require more materials. Int urch, renewables apart from nuclear don’t require materials for fuel cycles, so the results in this study are likely biased against renewables. The system will also result biased towards higher embodied emissions for nuclear given the inclusion of materials for fuel cycles. This implication was discussed in the relevant section, but we deemed the limitation itself acceptable at this point, since more uncertainty would have been introduced to the model had estimations of materials for fossil fuel cycles been made, particularly given the country-specific refining and pipelines. Research on those fossil fuel cycle materials is encouraged to expand the system boundaries. The limitations related to generic plant characteristics are taken from material inventories for each energy technology. We assumed that these generic characteristics are applicable to all the country electricity systems. However, some of these characteristics may be country- or location-specific, e.g., the cement required for the foundation of onshore wind turbines depending on the type of soil, the variable load factors for some power plants such as wind or coal, or the closer link between embodied emissions and built capacity of each technology-as opposed to the power output given the variable load factors. There is also a chance that once the variability of capacity factors in renewables is included in the normalised mass of materials per power output, the calculated mass of materials varies. This is because the normalised material amounts depend on a set capacity factor, which is likely different in the countries considered. We deemed these limitations to be an acceptable oversight at this point, since the material estimations are a good first approximation and would be the minimally acceptable for the systems, while engineers constructing these systems in each country will have access to detailed site and technology requirements. In turn, the technologies included in Mat-dp do not always differentiate specific types of the same energy technology category, e.g., gas power plants can use different turbine types. However, we considered that the values included in each technology were a good initial estimate, while the methodology allows for future refinement of technology types. Finally, the emission intensities considered are not country-specific values, but rather global averages. These quantities can then be improved in future studies of each country but are not currently hindering the conclusions of this paper around the need for material efficiency.

The limitations related to the application of Mat-dp to African countries includes the use of scenarios from one source. These scenarios, although rigorous, make assumptions such as the deployment of nuclear at levels which will require a high degree of stakeholder involvement to transform the systems. However, since the scenario source provides the required breakdown to country-level that this study required—considering that many scenarios are usually published at a regional or continental level—we found this to be an acceptable limitation. If future scenarios were developed at a country level, the methodology is well-placed to use them and evaluate their material implications.

6. Conclusions

This study has shown that planning for reductions in direct emissions via increasing the share of renewables is a priority for African countries, which should be accompanied by a joined-up strategy, where industrial capacity and trade are revised and embodied emissions of materials are reduced. The countries that need to implement the joined-up strategy sooner have been identified, thus reaping the highest benefits, given their high share (over 50%) of their power pool’s electricity demand and embodied emissions. The countries are Nigeria, Egypt, Ethiopia, Sudan, Tanzania, Kenya, South Africa, and the Democratic Republic of Congo. Several of these countries plus Algeria have also been identified as the largest cement producers in the region and can then also be prioritised in the strategy.

Opportunities to reduce embodied emissions in Africa to reduce material emissions have been proposed, including prioritising industrial decarbonisation, implementing material efficiency, and creating material pools. If these strategies are pursued, material emission savings can spill over to the buildings, transport, and industrial sectors, locking-in lower overall emissions over time. The actions to reduce emissions must also consider the climate risks for African electricity systems. Assessing electricity infrastructure risks has the potential to increase the reliability of electricity systems, while providing emission savings from avoiding the construction of new capacity to supply electricity when other systems fail.

This study has shown employment shifts that occur when changing electricity systems, highlighting opportunities for countries to address the resulting labour demand by regulating educational needs and gaps. Furthermore, countries that have historically relied on certain energy technologies have had to create plans for shifting labour, navigating a difficult path since it requires restructuring of local economies, e.g., Germany’s coal exit. In Africa, the results showed that there are opportunities to undergo changes in less painstaking ways, given the installation of new capacity and the jobs created by them.

Policy recommendations from this study surrounding material efficiency strategies in electricity generation are: to increase regional and international cooperation by creating regional material pools where key materials can be traded and by taking advantage of trade agreements, to monitor industrial efficiency, to encourage efficient manufacturing and management practices of scrap material, and to consider material life-cycles in design, manufacturing and planning.

Future work derived from this study is to improve the estimations of normalised materials per type of power plant so capacity instead of power output can be used, to find better data on embodied emissions for specific African countries, and to create databases of African material production, tracking local material efficiency and embodied emissions. These can lead to more accurate estimations of local systems and efficiency improvements. Storage, transmission and distribution, materials for decommissioning, materials for fuel extraction and processing for fossil fuels, and land use need to be included in the future projections, material requirements and the local databases, so their effect on
material requirements, competing land use priorities, and emissions may be studied alongside the generation technologies. To improve the sensitivity of this study, future work may try to include other scenarios for country level (when they are made available) or regional studies (provided they included the 47 countries included in this study in a discernible manner). Finally, future work may also include an uncertainty analysis of the materials used and embodied emissions.

Credit author statement

Karla Cervantes Barron: Conceptualization, Methodology, Data curation, Writing – original draft, Visualization. Maaike E Hakker: Conceptualization, Methodology, Data curation, Writing – review & editing. Jonathan M Cullen: Conceptualization, Writing – review & editing, Supervision.

Declaration of competing interest

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Appendix A. Supplementary data

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