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A Socio-Metabolic Assessment of Material Stocks in the Electricity Infrastructure*

by

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* Master thesis in Master programme Environment and Bio-Resources Management. This thesis was supervised by Univ.Prof. Dr.rer.nat. Fridolin Krausmann and Dipl.-Ing. Dr. Gerald Kalt of the Institute of Social Ecology.

Abstract

Global resource exploitation is a key driver of numerous environmental burdens and a decline of growing material inputs and outflows in form of waste and emissions is not in sight. Dematerialization efforts in the energy industry are particularly challenging, given that the opportunities of substituting electricity as an integral part of basic human activities are very limited. Recently, the material demand of energy generation technologies has been frequently analyzed, however, the electricity infrastructure remained largely neglected. One can expect a large-scale expansion of this infrastructure, owing to renewable energy deployment, increased access to electricity, and population growth. This work evaluates the material in-use stocks of the global electricity infrastructure, based on the methodical principals of material flow accounting, by using GIS data and multiple regression analysis. Global material stocks amount to 2184 ± 366 Mt and are anticipated to rapidly increase during the next decades. Significant amounts of copper of 165 ± 37 Mt are found with respect to the total in-use stocks and reserves. The construction of an electricity infrastructure especially in developing and emerging economies could be a challenge in view of synergistic achievement of Sustainable Development Goals, since increased electricity access triggers material demand and the associated carbon emissions. Reducing environmental impacts can be accomplished through resource efficiency and the decline of metal extraction and processing related CO_2-emissions.

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List of Abbreviations

AC – Alternative Current

ASRC – Aluminum Steel-reinforced Conductors

DC – Direct Current

EJ – Exajoule

EPR – Ethylene-propylene rubber

GHG-emissions – Greenhouse gas -emissions

GIS – Geographic Information System

Gt – Gigatons

kV – Kilovolt

kWh – Kilowatt per hours

LCA – Life Cycle Assessment

Mt – Million tons

MFA – Material Flow Accounting

OH – Overhead

OSM – Open Street Map

PE – Polyethylene

PVC – Polyvinylchloride

PV – Photovoltaics

RES – Renewable energy sources

SDG – Sustainable Development Goal

SSA – Sub-Sahara Africa

UG – Underground

UN – United Nations

1. Introduction

1.1. Relevance

Natural resource depletion is a foremost driver of environmental change such as global warming, biodiversity loss, and altered biogeochemical cycles (Steffen et al., 2015). Current consumption and production patterns and the related resource exploitation is unsustainable and the drastically growing material demand is considered as a root cause for irreversible and substantial damage to the earth´s natural environment (Schanes et al., 2019, Behrens et al., 2007). The biophysical limits thus must not be transgressed in order to prevent catastrophic effects for humanity (Rockström et al., 2009). Resource efficiency and dematerialization is vital to reduce both, the resource extraction and the material inputs in society, and the pressure upon planetary boundaries and the associated absorption capacity of ecosystems (Steffen et al., 2015, Schaffartzik et al., 2014).

Current global material extraction amounts to 89 gigatons (Gt; 1 Gt = 10^{15} g) annually and is projected to grow to 218 Gt by 2050 in a "global convergence scenario", largely driven by industrialization as well as population and economic growth (Krausmann et al., 2009, Krausmann et al., 2018). A sharp decline of material inputs and the dematerialization of the global economy is a prerequisite to cut carbon emissions and pave the way to sustainability (Allwood et al., 2013). However, the transformation to a low-carbon society is not straightforward as it requires the entire restructuring of economic activities including the transition towards a circular economy and the shift to clean energy technologies. Optimistic beliefs of socio-ecological development and the downward slope in the "Environmental Kuznets Curve" (meaning that economic growth is expected eventually to decrease environmental degradation caused in the early periods of economic development (Dinda, 2004)), sharply diverges from the actually growing inputs of energy and materials, and increasing production and consumption outflows in form of waste and emissions (Martinez-Alier, 2009, Hatfield-Dodds et al., 2017, Kaika and Zervas, 2013).

Concrete made out of cement is at present one of the largest drivers of global material consumption (Krausmann et al., 2017). Together with aluminum, steel, and copper, the highly energy-intensive manufacturing processes of those materials account to over 50% of global industrial CO_2-emissisons (IEA, 2008). Those materials are important constituents in the electricity infrastructure and high investments in power transmission and distribution systems expect an increasing demand of those materials. In 2018, investments in the transmission and distribution grid worldwide amounted to USD 300 billion with two thirds arising from investments in distribution grids and one third in transmission grids. The investments in power grids are, besides generation of renewable power, the largest part of global investments in the entire power sector, reaching almost 40%, primarily lead by China and the United States. Yearly expenditures in the grid are assumed to grow nearly up to USD 500 billion between 2025-2030 in order to meet rising electricity demand and GHG (greenhouse gas)-reduction targets through the utilization of renewable energy sources (RES) (IEA, 2019a). Besides population growth and the associated increase of energy consumption, the expansion of the grid is largely driven by two factors: the integration of RES in the electricity grid, and efforts for improved electricity access in developing and emerging countries (IEA, 2016, IEA, 2019a, IEA, 2019b)

First, the large-scale integration of clean energy technologies such as wind and photovoltaics (PV) entails the construction of wide-ranging intercontinental interconnection projects, which are essential to harness vast amounts of renewable energy due to the significant operational benefits of intercontinental power grids (Denny et al., 2010, Macilwain, 2010). This will be of vital importance in the implementation of RES, which are not only intermittent in their nature, but also abundant in remote locations such as offshore or in deserts (Brinkerink et al., 2019). The extension of the high voltage transmission grid to bring RES to consumers has thus a central role, as it can improve grid stability and reduce transmission losses. Additionally, it is more cost-efficient than current systems as it reduces the requirement for expensive storage systems and gas power plants for peak loads (Chatzivasileiadis et al., 2013). Moreover, the launch of electric vehicles and heat pumps further entails the electrification of the energy sector, and if growing energy demand coincides with GHG-reduction targets, the electricity infrastructure will gain increasing importance (Saidi et al., 2017, Kempton and Tomić, 2005). It is expected that the electricity sector will witness substantial growth, from a current share of 20% to 42% in 2050 (Rogelj et al., 2015).

Second, the United Nations (UN) have proclaimed universal access to affordable and clean energy by 2030 as a Sustainable Development Goal (SDG). Particularly developing countries in Sub-Sahara Africa (SSA) are still suffering from low electrification rates and the related impediment of socio-economic progress (Chirambo, 2018). Electrification and universal energy access are commonly perceived as fundamental for achieving desirable objectives, including poverty and malnutrition alleviation, improved health care and education, and increased gender equality (IIASA, 2018, Obermaier et al., 2012). Poor countries with high development aspirations therefore rapidly seek for prosperity, and have observed remarkable growth rates of energy consumption and improved energy access in the last two decades (WB, 2019). Despite considerable efforts during the last years, around 600 million people in Africa are struggling with insufficient access to electricity. Thus, investments not only in renewable energy, but also in the electricity infrastructure will require a yearly amount of up to USD 55 billion to meet the growing demand and ensure universal energy access by 2030, especially in SSA (IEA, 2019c). This corresponds to a seven-fold increase from current investments (Johnson et al., 2017, Schwerhoff and Sy, 2017). Additionally, climate targets from the Paris Agreement to prevent global warming of more than 2°C oblige a RES share on electricity of 70% in 2030 and 100% in 2050. Therefore, in compliance with the Paris Agreement, developing countries need to leapfrog in renewable energy systems (IIASA, 2018). This highlights the future demand for considerably enlarging the electricity infrastructure.

Due to the ongoing transformation of the electricity sector towards RES as well as rising demand and increased access to electricity, the International Energy Agency approximates additional power line lengths of 23 million km by 2030 (IEA, 2012). However, scholars have widely neglected the increasing material demand for expanding electric power systems and the accompanying environmental impacts. For that reason, it is crucial to assess the resource use related to the globally expanding electricity infrastructure. Especially high voltage transmission systems are highly material intensive, and, given the transformation to renewable energy, continuous population growth, and growing access to electricity, more emphasis should be put on the environmental consequences regarding the establishment of the electricity infrastructure.

In previous research, limited focus was put on the quantification of resources used for the electricity infrastructure. LCA-based approaches of environmental impact assessments of power grids have been merely undertaken for few countries, including Denmark (Turconi et al., 2014), Great Britain (Jones and McManus, 2010) Switzerland (Itten et al., 2012), California (Bumby et al., 2010), and Norway (Jorge and Hertwich, 2013). Environmental impacts of the grid expansion driven by RES integration within the EU has been studied by Jorge and Hertwich (2014). However, earlier studies were based on methods of life cycle assessments and evaluated effects in environmental categories such as terrestrial acidification, ozone depletion, climate change, or land use. None of the publications gives a comprehensive overview about the quantity of material stocks on a global level. A notable exception is Ecofys (2014), who provides rough estimations of global copper stocks in distribution lines and cables.

1.2. Research aims

Since the electricity infrastructure is rich in iron, zinc, copper, aluminum, concrete, timber, plastics, and paper (Krook et al., 2011, Itten et al., 2012, Jorge and Hertwich, 2013, Bumby et al., 2010), it is argued that it may incorporate a significant amount of those resources. Moreover, the sustainable development goals “Affordable and Clean Energy” (SDG 7), “Responsible Resource Consumption and Production” (SDG 12), and “Climate Action” (SDG 13), may stand in contrast to each other. This may be the case due to the introduction of renewable clean energy and growing access to electricity in developing and emerging countries. Growing material requirements due to the expansion of electricity transmission and distribution systems may lead to unsustainable resource use and GHG-emission from the production of those materials.

This master thesis presents a first quantification of global material demand for building the electricity infrastructure for power transmission and distribution, based on the conceptual and methodological principles of material flow accounting (MFA), embedded in the concept of the social metabolism. The aim is to quantify material in-use stocks of the electricity infrastructure. The scope of this work comprises high voltage transmission, medium- to low voltage distribution lines and cables, power towers, and their respective foundations and cable ducts, which are considered to be the most relevant parts of the electricity infrastructure. The geographical scope comprises a global assessment with details on country level and further information on the spatial distribution of material stocks. Particular emphasis is given to material stocks of the transmission and distribution system in the Europe and to the global transmission system. Moreover, this work estimates future trends of material demand. Results are compared to total in-use stocks and respective available reserves and resources to gain insights into the significance of electricity infrastructure related material consumption. Eventually, synergies and trade-offs of SDG 7, SDG 12 and SDG 13 are discussed and proposals for reducing material demand are given.

The guiding questions of this thesis are:

- What is the size of material stocks in the current electricity infrastructure and what is their share related to global material stocks differentiated by material types, based on the year 2019?
- How does projected material demand for the electricity infrastructure relate to historic extraction rates, particularly under the premise of universal access to clean energy (SDG 7)?
- Should material demand for the electricity infrastructure be considered as impeding factor to other Sustainable Development Goals, especially SDG 12 (“Responsible Resource Consumption and Production”) and SDG 13 (“Climate Action”)?

The structure of this work is as follows: It starts with an introduction to the concept of the social metabolism and MFA, which are the theoretical foundations of this work (section 2). In the methodology section (3), the components of the electricity infrastructure which are considered here are described. Then, the methodical approach and data for calculating line lengths and their material composition and mass are presented. The results section (0) presents the quantities of material in-use stocks on a global scale with special focus on Europe. The results are subsequently discussed and put into the proportion of total in-use stocks, total reserves and resources to evaluate the significance of material stocks in the electricity infrastructure (section 5). Moreover, opportunities for reducing material demand are examined. Finally, the results are discussed in the context of the SDGs and concluding remarks are given.

2. Theoretical and scientific classification

The following sections give a brief synopsis on the concept of the social metabolism (2.1.) and material flow accounting (2.2.), which is the scientific background of this thesis. It presents the theoretical perspective and clarifies central terms that are related to social ecology.

2.1. Social metabolism

In the course of dematerialization, the increasing demand in environmental and sustainability sciences for inter-, and transdisciplinary research, and a more comprehensive perspective of socio-ecological challenges of society, has led to a range of new concepts (Baumgärtner et al., 2008). Environmental literacy has a key role in understanding the interlinkages of biophysical and social traits, and the communication to policy-makers (Pauliuk and Hertwich, 2015). In the context of global environmental change and sustainable development, these concepts include the “social metabolism”. The term “metabolism”, which actually denotes to the sum of “chemical reactions and physical changes that occur in living organisms” (Cammack et al., 2004), was taken on by scholars studying the quantification of material stocks and flows (Baccini and Brunner, 2012). Various definitions emerged such as from Fischer-Kowalski and Amann (2001), who described it as “the sum of total material and energetic flows into, within, and out of a socio-economic system”, and from Baccini and Brunner (2012), as “all physical flows and stocks of energy and matter within and between the entities of the space in which biological and cultural activities of human beings take place”.

The social metabolism therefore studies the linkage between socioeconomic and biophysical processes, hence, evaluating the effects of society-environment interactions. Fig. 1 illustrates this relationship between the natural environment and socioeconomic action. Social metabolism is an interdisciplinary integrated assessment for analyzing biophysical stocks and flows as well as the services they provide to society (Haberl et al., 2019). It links ideas from various scientific disciplines such as economics, technology, and biology, to gain valuable insights in the relationship of human behavior and natural systems. Knowledge of the social metabolism can provide an essential scientific foundation that underpins policies for a reduced environmental footprint, as it illustrates the material and energy flows associated with human activity. It thus can be considered as an important indicator for sustainable resource use (Bornhöft et al., 2016).

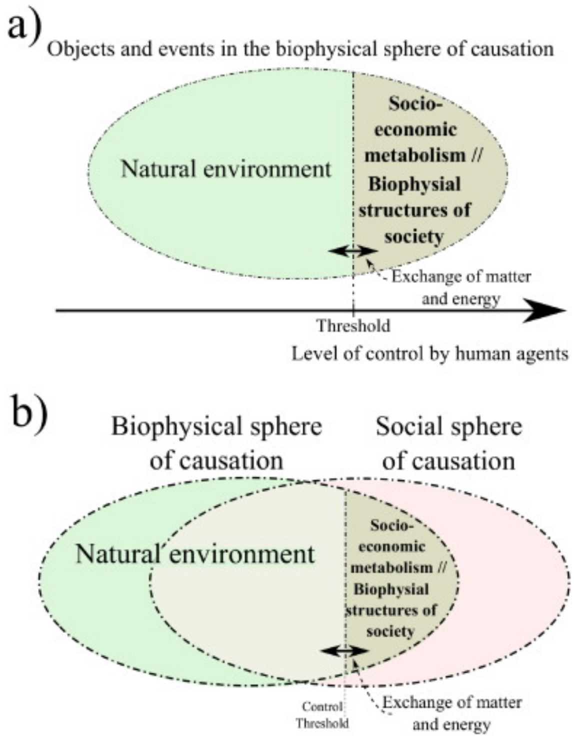


Figure 1: The social metabolism as a link between natural and social systems. Source: Pauliuk and Hertwich (2015).

The concept of socioeconomic metabolism has gained significance in environmental sustainability research, and is expected to play a key role in the background of increasing ecological awareness (Haberl et al., 2017). The limits of this concept are its lack of ability to account for social dynamics such as altered consumption patterns due to the change of consumer lifestyle and the related consumption level. Methodical approaches to assess the metabolic transition include Life Cycle Assessment (LCA), Input-Output Analysis, Integrated Assessment Models, General Equilibrium Models, and Material Flow Accounting (MFA) (Pauliuk and Hertwich, 2015). Bottom-up assessments of material stocks such as the one performed in this work can be considered as supplementary methods to the field of MFA, as they can further strengthen our understanding of materials stocks and their functions.

2.2. Material Flow Accounting (MFA)

The basic notion of material flow accounting goes back to a concept that was first designed by Ayres and Kneese (1969), who argued that the economy largely relies on common free goods – for example water and air – , hence, prevent pareto-optimal allocations of goods. They claimed that consumption and production patterns and the associated market failure are the outcome of the disregard of the law of mass balance. Hence, they put forward an inclusive view of environmental pollution and take account of mass conservation. In a closed economy, where there are no exports or imports and no accumulation of stocks, the law of conservation of mass requires the “amount of residuals inserted into the natural environment must be approximately equal to the weight of basic fuels, food, and raw materials entering the processing and production system, plus oxygen taken from the atmosphere” (Ayres and Kneese, 1969). In the 1990´s, scholars in Japan (National Institute for Environmental Studies), Germany (Wuppertal

Institute) and Austria (Institute of Social Ecology) first began with scientific works in MFA. During the following years, MFA experienced methodical and conceptual progress, research networks emerged, and indicators were specified (Fischer-Kowalski and Hüttler, 1998, Fischer-Kowalski et al., 2011).

Material flow accounting is a an approach for purely physically modelling the resources' use of socioeconomic systems (Pauliuk and Hertwich, 2015). The system boundaries comprise the extraction of materials and energy from the natural environment, their use for supplying goods to society and maintaining, operating and expanding artefacts such as buildings, factories, machinery or infrastructures. Eventually, materials and energy are discharged into the environment as wastes and emissions (Haberl et al., 2019). Materials at their highest level of aggregation are commonly categorized into biomass, fossil fuels, industrial minerals, metal ores, and bulk materials for construction (Fischer-Kowalski et al., 2011)

Fig. 2 shows a schematic illustration of the economy-wide material balance model. The domestic material consumption is the sum of materials from domestic extraction and imports minus exports. The domestic processed outputs are emissions and waste from production and consumption processes, the deliberate deposition, and dissipatively used materials.

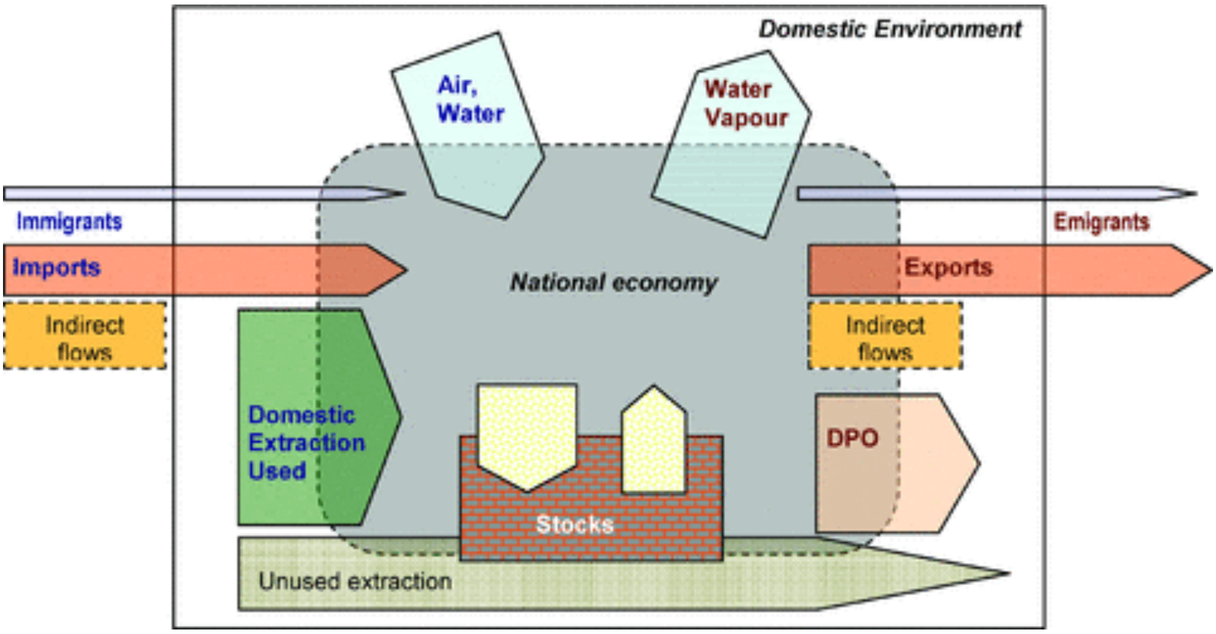


Figure 2: Material mass balance model. Source: Fischer-Kowalski et al. (2011).

In recent times, economy wide-MFA has been advancing. Previously, it did not include in-use material stocks of manufactured capital (i.e. all artifacts including buildings, infrastructures, machinery, all types of durable goods). It put its emphasis on the flows of material and energy, hence, general framework conditions for the transformation of resource use were absent. Recent works have focused on both, ties of flows and inventories of materials, and the services that offer specific arrangements of stocks and flows. It characterizes inventory and service indicators, and by virtue of wide-ranging data banks, the nexus of stocks and flows is scrutinized (Haberl et al., 2017). Thus, the in-use stocks of material flows and manufactured capital and waste have been incorporated in the MFA framework (Wiedenhofer et al., 2019). Besides MFA, the energetic metabolism can be analyzed by energetic flow analysis (EFA). In addition to traditional energy statistics, the required energy to nourishing humans and livestock as well as inputs of energy-rich materials that pass through borders of the considered metabolism are incorporated into EFA, irrespective of their objective (Haberl et al., 2006, Haberl, 2001).

During the last decades, the creation of large databases has led MFA to maturity and allows for proper analysis of resource use at the interface of society-environment interactions (Fischer-Kowalski et al., 2011). If combined with historical data, it enables to demonstrate the metabolic transition over time, as it provides information of amount and composition of resource use with respect to socioeconomic development (Krausmann et al., 2008). Additionally, the MFA databases can be used in combination with traditional economic models to assess environmental impacts in economic systems (Schandl and Turner, 2009).

The socioeconomic metabolism has been analyzed by MFA at different spatiotemporal scales, ranging from the global economy (Krausmann et al., 2018), to country level analysis of India (Singh et al., 2012), China (Zhang et al., 2012), and Scotland (Viglia et al., 2017). Also certain sectors were analyzed such as the road network in the United States (Miatto et al., 2017). Its focal point is the socio-ecological transformation and environmental history research that has significantly shaped the sustainability discourse in recent years (Haberl et al., 2019).

3. Methodology and data

The following sections describe the methodical approach to assess material stocks of electricity infrastructures. It explains how line lengths are calculated (section 3.3.1) and provides data regarding the material intensity of power lines (section 3.3.2). The first sub-section (3.1) gives information about the function of the electricity infrastructure, its installation and construction, and components that are considered within this work.

3.1. The electricity infrastructure

This sub-section provides a short description of the function of the electricity infrastructure and its components. The term "electricity infrastructure" includes constituents and facilities that are necessary to transmit and distribute electricity from generators to consumers. A clear distinction from this term is difficult and its extent is not entirely clear. Here, components that are considered in this work are explained, and distinctions into overhead (OH) lines and underground (UG) cables as well as into transmission and distribution systems are elucidated. The following explanations are based on Short (2004).

In electrical power engineering, the electricity grid refers to a network for the transmission and distribution of electrical energy. It consists of electrical OH lines and UG cables and facilities including switchgear, busbars, transformer stations, and substations. The purpose of electricity transmission and distribution is to transport electricity from power generation plants to consumers. This should be achieved in a most reliable, safe, and cost-efficient way with a minimum of power losses.

The high voltage transmission network transmits electricity generated by power plants and fed into the grid nationwide, to power transformers that are close to the main consumption points. It is required for the transmission of electricity across large spatial distances and is thus characterized by high voltage levels. Electricity lines under high voltage can transmit energy more efficiently than low voltage lines, with reduced amperage and voltage drop, and therefore reduced losses. The ability of carrying more capacity with a reduced voltage drop allows to encompass a more widespread operating region, consequently, the necessity of substations is reduced. The medium voltage network distributes the electrical energy to the regionally distributed transformer stations or larger facilities, such as hospitals or factories. Public utilities, which also operate smaller power plants, also feed their electricity into the medium voltage network. The low voltage network is responsible for the distribution of the electricity to the end consumer. The low voltage in Europe is transformed to the usual 230V/400V, hence private households, small industrial companies, businesses, and administrations are supplied.

Power lines are further classified in OH lines and UG cables. OH lines are constructed on masts above ground, and UG cables are built below ground in cable ducts or conduits. Each have their advantages and disadvantages. The major advantages of OH lines are (a) their costs, as they are much more inexpensive and last longer than cables (30 to 50 years vs. 20 to 40), (b) they are more reliable, owing to easier and faster fault finding and repair in case of power outages, and (c), their greater ability to resist overloads. UG cables, however, are often preferred due to less visual impacts, especially in urban areas. In addition, power outages occur fewer and the safety is higher due to less public contact. Moreover, cables are characterized by lower voltage drop due to their smaller reactance and lower maintenance costs.

3.2. Considered components

Power lines and cables

The components of lines and cables that bring electricity from generators to consumers consist of more than just the conductor that transmits electric power. Fig. 3 illustrates a typical structure of an UG cable. In the middle, the conductor-wires are covered by a shield. This is surrounded by the insulation and the respective shield. The external layer is the covering jacket.

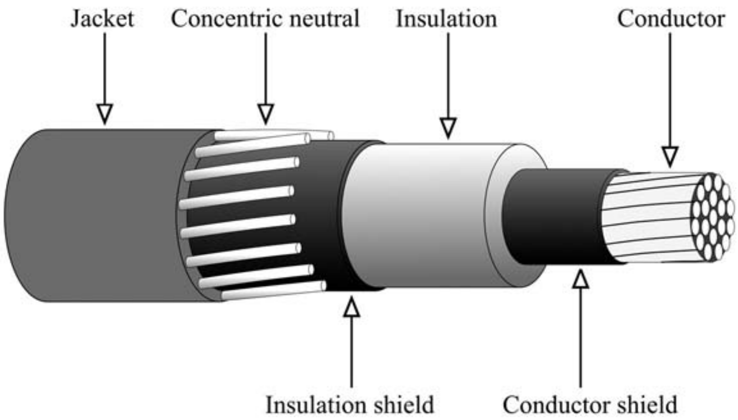


Figure 3: Components of an underground distribution cable. Source: Short (2004).

The conductor is the central component of the electricity infrastructure. It consists of wires that carry the electric current and is usually made of either aluminum or copper. The latter is characterized by a higher ampacity, higher corrosion resistance, and lower resistivity, but aluminum is lighter and cheaper for a given capacity. In the past, copper conductors were used much more frequently, so there are still large numbers of copper conductors in service; however, the vast majority of new installations are aluminum conductors. Nevertheless, copper is preferably used in UG cables because in this case the weight is irrelevant. Due to its lower weight, aluminum is predominantly used for high voltage capacities, as reduced weight means that larger distances between towers are possible.

There are several types of aluminum conductors:

- AAC — all-aluminum conductor: greatest conductivity-to-weight ratio of all overhead conductors
- AAAC — all-aluminum alloy conductor: suitable for coastal areas due to lower corrosion
- ACAR — aluminum conductor, alloy reinforced: the alloy strands lead to improved mechanical strength
- ACSR — aluminum conductor, steel reinforced: very high mechanical strength, hence, can tolerate higher wind and ice loads. Usually applied in the highest voltage level.

The aim of the insulation is to restrain the outflow of electrons. During the 20th century, paper with impregnated insulating oil was primarily utilized for cable insulation with the sheath made out of lead. The lead sheath is well-suited for exclusion of water and oil. Both, the paper insulation and lead sheath were largely employed in urban regions. Since the 1970s, the insulation of cables was largely replaced by polyethylene (PE) such as cross-linked polyethylene (XLPE) and ethylene-propylene rubber (EPR) composites. The sheath is the layer that covers the cable insulation and consists mainly of copper or lead. It protects the cable from current from other fault sources and provides a return current for fault current. Moreover, it protects from lightning strikes. The most common material used for jackets is polyvinyl chloride (PVC). PVC has good jacketing skills as it prevents moisture from entering the cable and has suitable mechanical and heat properties.

Installation and construction

Particularly in medium- and low voltage distribution, wood poles are mostly employed as masts that hold the lines. They are characterized by long lifetimes, easy access for maintenance, and improved insulation between conductors and ground. Considering high voltage transmission networks, mostly steel lattice towers are used. Steel lattice towers are set in concrete or steel-reinforced concrete to ensure stability. The distance between the towers rises according to the voltage level and therefore also the requirements for improved stability. Hence, the material requirements for the foundation and masts rises according to the voltage level.

Cables are often encased in ducts or conduits, especially in urban areas. Conduits are again covered in concrete that protects the conduit from shifting earth and avoids dig-ins. They can be repaired or replaced faster, hence power outages are shorter. They are generally made of PVC. Additionally, concrete enclosed cable ducts have a good surge protection. Cable ducts can incorporate PVC enclosed in concrete.

This work takes into account conductors of OH lines and UG cables, their respective insulation, insulation shield, and the jacket. Additionally, the power towers (masts) of overhead lines and their respective foundations are considered as well as the cable ducts, cable trace and conduits. It encompasses the assessment of the high voltage transmission, the medium voltage and the low voltage distribution grid on a global scale. It does not take into account material requirements of transformers, busbars, substations, switchgear, power bays or generation plants.

3.3. Calculation of material stocks

The assessment of material stocks in the electrical energy infrastructure on a global level involves the calculation of power line lengths and the material intensity of one unit of line length. Because the material intensity of power lines can vary substantially with respect to their voltage level, the length of the high voltage transmission lines, the medium voltage and low voltage distribution lines have to be calculated separately. Further, material requirements for OH lines and UG cables are different in each voltage level. Section 3.3.1. explains how the electricity grid is split up and how lengths of OH lines and UG cables in the respective voltage level are calculated to account for different material stocks in the electricity infrastructure. In section 3.3.2, data about material intensities differentiated by voltage levels and OH lines and UG cables are provided.

3.3.1. Calculation of power line lengths

The calculation regarding the length of power lines of the entire electricity system disassembles in the assessment of the transmission and the distribution system due to different methodical approaches. Owing to the fact, that official statistical data of countries are limited, the length of the transmission system was obtained using GIS data. The distribution system was estimated via multiple regression analysis based on statistical data for European countries, India, Indonesia and USA.

Herein this work, the term "high voltage transmission system" refers to the infrastructure with a voltage level above 100 kV, "medium voltage distribution system" to 1-100 kV and the "low voltage distribution system" refers to the residual system below 1 kV. The term "transmission system" used in this work refers to the infrastructure components above 100 kV, and the term "distribution system" refers to components of equal 100 kV and below.

High voltage system

High voltage transmission line lengths are extracted from OpenStreetMap (OSM) data. The OSM-initiative (available on the website https://www.openstreetmap.org) is a free project that collects, structures and maintains freely usable geodata in a database (open data). This data is under free license, the open database license. Besides a range of other things, volunteers of the OSM-initiative have developed a global map of large parts of the electricity infrastructure. However, extraction of the relevant global data layers from OSM data is very hardware intensive. In order to obtain the relevant electricity infrastructure data, the total OSM data (also streets, restaurants, facilities, etc.) which amounts to over 80 gigabytes needs to be downloaded, filtered and separated into different categories. Limited computing power prevented the download of such large data record. Rather than extracting them directly from the OSM database, they were provided on request by Detlev Reiners from 123map GmbH & Co.KG (contact information is available on the website https://www.flosm.de and was found after internet research). The company 123map GmbH & Co.KG. exports data regarding the electricity infrastructure regularly for customers and offers the OSM data free of charge for students and academic research purposes. The data of April 2019 was obtained on the 12th August 2019.

The data was transferred into the program QGIS 3.10 (an open source geographic information system). In order to prove the suitability of the OSM data, the line length of selected industrialized countries was calculated and compared to official national statistics (industrialized countries were chosen because of easy accessibility to official national statistics). The comparison to national statistics of Ireland, Japan, USA, and Austria revealed that high voltage power line lengths (lines above 100 kV) are relatively consistent with national statistics, whereas power lines below 100 kV showed increasing deviation from official data. Therefore, it was decided to only use power lines above 100 kV from the OSM data.

Hereafter, continents were cut out and divided into Europe, Asia, Africa, Latin America, North America, and Oceania. The designation "Europe" refers to countries of the European continent and not only member states of the European Union (for detailed list see Appendix A). The line length of the AC (alternative current) and DC (direct current) power lines were calculated in the program QGIS and transferred to spreadsheets. Due to a coherent classification by voltage levels, the length of lines higher than 100 kV could be calculated. The high voltage transmission lines were further subdivided into highest voltage level with 1000 kV or higher, 600-800 kV, 500-600 kV, 400-600 kV, 300-400 kV, 200-300 kV and 100-200 kV. This division was chosen in order not to exceed a reasonable amount of work in data preparation. Finally, the length of lines and cables was calculated and categorized into 100 kV and 350 kV or higher and could thus be clearly displayed on their respective continents. The categorization in 100 kV and 350 kV was done in view of available data regarding differences in material intensity of high voltage systems. This means that material demand of high voltage lines is subdivided into two parts: lines between 100 kV and 350 kV (1), and lines higher than 350 kV (2).

Electricity transmission and distribution in Eurelectric member states

The Eurelectric member states comprise all member states of the European Union plus Norway. "Eurelectric" refers to the Union of the Electricity Industry, which is the sector association that represents the common interests of the electricity industry on a European level. It has published a statistical report with comprehensive data in its member states (see Eurelectric, 2011). This report provides data on total line lengths of UG cables and OH lines of the transmission and distribution system of each member state. In the report, the grid is divided into < 1kV as low-voltage distribution, 1-100 kV as medium-voltage distribution, and > 100kV as high-voltage transmission system, which is consistent to this work. So, there is official data from Eurelectric member states about the length of OH lines and UG cables in the low-, medium-, and high voltage system, which makes it easy to calculate the material stocks of these systems.

Global low-, and medium distribution system

On the basis of Eurelectric data for European countries and official national statistics of India, Indonesia and USA, a regression model was developed with which the line and cable lengths for the remaining countries were estimated. The dependent variable was estimated by the following equation (1):

$$Y_{TLL} = \alpha + \beta_1 X_{popaccesselec} + \beta_2 X_{popdensity} \quad (1)$$

where Y_{TLL} is the total line of a given country. $X_{popaccesselec}$ stands for the population with access to electricity and $X_{popdensity}$ for the population density in the respective country. Data about the population, the percentage of population with access to electricity, and the population density of countries were obtained from the World Bank (WB, 2019). For each country, the number of the population was multiplied with the percentage that has access to electricity to account for the weaker developed electricity infrastructure in developing and emerging countries. Next, the length of the total transmission and distribution power lines on a global level was calculated. This was achieved by multiplying the regression coefficient with the respective parameter and adding the intercept. The global length was obtained through the summation of the line length of each country.

The global length of the electricity grid served as a basis for the subsequent calculation regarding the length of OH lines and UG cables in low-, and medium voltage systems (the length of high voltage systems was already calculated through GIS data). This was achieved by calculating the relative percentage share of low-, and medium voltage power lines in each Eurelectric member state based on the data from Eurelectric (2011). Hereafter, the mean value of the percentage share of OH lines and UG cables in the low-, and medium voltage system was calculated. Since the relative proportions vary by country, the 95% confidence interval of the mean value was calculated. This was done by determining the standard deviation (SD). Based on the SD, the standard error of the mean (SEM) was obtained using equation 2:

$$SEM = \frac{SD}{\sqrt{df}} \quad (2)$$

After calculating the critical t-value (t(crit), the 95% confidence interval was obtained from equation 3:

$$95\%\ \text{conf.} = \text{SEM} * \text{t(crit)} \quad (3)$$

The lower and upper limit of the 95% confidence interval was obtained by subtracting from or adding the 95% confidence interval to the mean value. The lower limit refers to the notion “low”, the mean to “mid” and the upper limit to “high”. The values were multiplied with the total length from the regression analysis, hence, the line length of OH lines and UG cables in the respective voltage level on a global scale was obtained.

Summary of approaches

In summary, the line lengths of the Eurelectric member states were calculated by using official statistical data of Eurelectric (2011). This data was used to build a multiple regression model together with official data of India, Indonesia and USA (no further data of other countries were incorporated due to lack of available official statistics). The regression model was used to calculate the total line lengths for countries of the rest of the world (all other countries than the Eurelectric member states plus India, Indonesia, and USA) on country-level with the explanatory variables of population that has access to electricity and population density. The share of OH lines and UG cables in the low-, and medium voltage level (< 1kV, and 1-100 kV respectively) of Eurelectric member states were calculated along with their respective 95% confidence interval. Based on the 95% confidence interval, the low-, medium-, and high share was multiplied with the total line length, therefore, the estimated range of the line length regarding the OH lines and UG cables in the respective voltage level was obtained. The high voltage lines were calculated by GIS data obtained from the OSM-initiative. Table 1 gives an overview on different methods used to assess global line lengths in their respective voltage level.

Table 1: Summary of approaches used for deriving global power line lengths.

	< 1 kV	1-100 kV	>100 kV
Eurelectric member states	Statistical Data	Statistical Data	Statistical Data
Europe	Linear Regression	Linear Regression	GIS-based
North America	Linear Regression	Linear Regression	GIS-based
Asia	Linear Regression	Linear Regression	GIS-based
Latin America	Linear Regression	Linear Regression	GIS-based
Africa	Linear Regression	Linear Regression	GIS-based
Oceania	Linear Regression	Linear Regression	GIS-based

3.3.2. Material requirements of power lines

In this section, material intensities of the electricity grid are shown. To account for consistency according to the line length, the electricity grid was again divided into the three voltage categories of low voltage that refers to voltage levels equal or lower than 1 kV, medium voltage that refers to voltage levels equal or above 1 kV and equal or under 100 kV, and high voltage that refers to voltage levels above 100 kV.

Since this work assesses the material stocks in each voltage level and further differentiates into OH and UG in each voltage level, the choice of an appropriate value for each part of the distribution system is not straightforward. The difficulty arises from the fact that different studies do not always provide complete information on the total material consumption, and the data therefore have to be collected from several studies. In order to be able to use consistent data (higher voltage levels require usually more material), and all components of the infrastructure including lines, the insulations and their foundations, towers, as well as cables and cable ducts, are taken into account (see also section 3.2), material intensities are adopted from three studies: Data on material intensities in the distribution system are adopted from Bumby et al. (2010) and Itten et al. (2012), and in the high voltage transmission system from Jorge and Hertwich (2013). For comparison, data from further studies are also included in the following paragraphs and tables.

Table 2 shows material requirements for the assessment of material stocks for the low voltage OH lines. It is assumed that copper is used as a cable conductor for both, UG cables and OH lines. There are significant differences especially regarding material requirements for conductors. Itten et al. (2012) and EWZ (2011)[1] assume relatively high copper values compared to other authors whereas Jones and McManus (2010) and Bumby et al. (2010) report significantly lower values. The impression that the values from Itten et al. (2012) and EWZ (2011) are rather high is supported by a report of Ecofys (2014), who assume copper requirements of 2000 kg km^{-1}, or Arvesen et al. (2015), who calculate with copper values of 500-1500 kg km^{-1}. This work adopts the copper intensity according to Bumby et al. (2010). Further, it is assumed that the masts

[1] Personal communication according to Itten et al. (2012)

consist of wood poles. The value is adopted from Itten et al. (2012) with the wood density of timber of 650 kg m^{-3}. The residual values for steel, lead, PVC, paper, and mineral oil are also adopted from Itten et al. (2012).

Table 2: Material requirements for low voltage overhead lines (in kg km^{-1}).

	Line + Insulation						Masts
	Copper	Steel	Lead	PVC	Paper	Mineral oil	Timber
EWZ (2011)	4590	1	2111	1012	446	399	
Itten et al. (2012)	4600	1	2100	1000	450	400	5200
Jones and McManus 2010	2665						
Bumby et al. (2010)	1414						
Ecofys (2014)	2000						
Arvesen et al. (2015)	500-1500						
This work	**1414**	**1**	**2100**	**1000**	**450**	**400**	**5200**

Table 3 shows values for UG cables, their insulation, and installation. Regarding copper, the value is again adopted from Bumby et al. (2010). It is further assumed that the cable duct is built out of concrete. Itten et al. (2012) assume a relatively high value for concrete with 70400 kg for the cable duct and Jones and McManus (2010) calculate the material consumption of the cable duct which is filled with gravel with 53325 kg per km. Here, the same material demand for the cables and insulation is used for the OH lines and is adopted from Itten et al. (2012). The requirement for steel, resins, and plastics is also adopted from Itten et al. (2012). Since in this work the assumption is made that the cable ducts is made completely out of concrete, the values for concrete from Itten et al. (2012) in the medium voltage level would be lower than in the low voltage level, which is not reasonable. Thus, the somewhat lower value from Bumby et al. (2010) is adopted for the low voltage system, to subsequently use the concrete value of Itten et al. (2012) for the medium voltage system and account for growing concrete demand. The density for concrete is assumed to be 2200 kg m^{-3}, which is adopted from Itten et al. (2012).

Table 3: Material requirements for low voltage underground cables (in kg km^{-1}).

	Line + Insulation						Cable duct			
	Copper	Steel	Lead	PVC	Paper	Mineral oil	Steel	Concrete	Resins	Plastics
EWZ (2011)	4590	1	2111	1012	446	399	1			
Itten et al. (2012)	4600	1	2100	1000	450	400	1	70400	25	25
Jones and McManus (2010)	2665									
Bumby et al. (2010)	1414							17134		
This work	**1414**	**1**	**2100**	**1000**	**450**	**400**	**1**	**17134**	**25**	**25**

Table 4 gives information about the material use of OH lines in the medium voltage system. EWZ (2011) combined two different data sources from Bumby et al. (2010) and Jones and McManus (2010), and calculated an average value for copper, steel, timber, and porcelain. All data about the material requirements were directly adopted from Itten et al. (2012), who largely adopted the values from EWZ (2011). In absence of reliable data, a 50/50 split between copper and aluminum is assumed which is further assumed for the medium voltage UG cables. Owing to the fact that aluminum is lighter in its weight, the value is lower compared to copper.

Table 4: Material requirements for overhead medium voltage power lines (in kg km^{-1}, except for timber in m^3).

	Lines + Insulation				Cable reels, brackets and masts		
	Copper	Aluminum	PE	Silicon rubber	Steel	Porcelain	Timber
Jones and McManus (2010)	4663	1889	56	30	1079	134	7.9
Bumby et al. (2010)	-	940	28	15	768	-	8.7
Itten et al. (2012)	2330	940	28	15	923	67	8.3
This work	**2330**	**940**	**28**	**15**	**923**	**67**	**8.3**

Table 5 shows the material intensity of the UG medium voltage system. The values are completely adopted from Itten et al. (2012).

Table 5: Material requirements for underground medium voltage power lines (in kg km^{-1}).

	Cables				Cable duct			
	Copper	Aluminum	PET	EPR	Steel	Resins	Plastics	Concrete
Jones and McManus (2010)	2665	4081	507	1089	-	35	35	
Bumby et al. (2010)	1414	4180	4598	-	11300	-	-	-
EWZ (2011)	4274	-	828	-	21	-	-	27060
Itten et al. (2012)	2784	2754	1978	363	21	25	25	26400
This work	**2784**	**2754**	**1978**	**363**	**21**	**25**	**25**	**26400**

Jorge and Hertwich (2013) provide comprehensive data about material intensities for the high voltage transmission system (Table 6). They further divide into two the voltage levels 150 kV and 400 kV, with 400 kV-systems featuring between 31% (concrete) and 700% (zinc) higher specific material intensities than 150 kV-systems (however, material intensity of steel for insulators and mineral fat in 400 kV-systems feature 4 and 23% lower values). The foundation is assumed to be a steel reinforced concrete foundation and the masts consist of steel with zinc coating to prevent corrosion. The insulation is mainly made out of hard glass, which is similar to porcelain used in medium voltage OH lines. The conductors are made out of steel reinforced aluminum, which is characterized by a very high mechanical strength, hence it can tolerate higher wind and ice loads. They are commonly implemented in high voltage lines. This work uses the values of 150 kV for lines between 100 kV and 350 kV, and the values of 400 kV for lines of 350 kV or higher.

Table 6: Material requirements for high voltage overhead lines (in kg km^{-1}). Source: Jorge and Hertwich (2013).

		150 kV	400 kV
Foundation	Concrete	129600	288000
	Iron	6000	15000
Masts	Steel	18000	53000
	Zinc	200	1600
Insulators	Hard glass	562	1350
	Steel	852	816
	Cement	48	63
Conductors	Steel	2570	4320
	Aluminium	7020	11940
	Mineral fat	490	378
Earth conductor	Steel	460	928
	Aluminium	280	556
	Mineral oil	14	28

Jorge and Hertwich (2013) provide further information on material requirements of high voltage UG cables in 150 kV-systems (Table 7). Copper is the material used in the conductors surrounded by the insulation and the sheath made out of lead. The cable trace is made out of concrete, sand and asphalt. This only applies to high voltage cables onshore, meaning that the sea cables are neglected in this work. This is owing to the lack of designation of sea cables in the GIS data. Thus, the line length of the sea cables cannot be evaluated and high voltage UG cables offshore and onshore are packed together. Due to the lack of available data, it is assumed that the data applies to every high voltage level (higher than 100 kV).

Table 7: Material requirements for high voltage underground cables (in kg km^{-1}). Source: Jorge and Hertwich (2013).

Cable	Copper	8600
	Paper	3800
	Insulation oil	4000
	Lead	13900
	Bronze	3200
	Asphalt	700
	PP	1900
Cable trace	Sand	1600000
	Concrete	35000
	Asphalt	75000

Having data regarding material intensity of OH lines and UG cables for the transmission and distribution system as well as the respective line length, the material stock could now be calculated.

4. Results

This section features results of material requirements of the global electricity infrastructure, and is structured as follows: first, results regarding the global high voltage transmission infrastructure based on GIS data are presented (section 4.1). After that, results regarding the material demand of the transmission and distribution system within Eurelectric member states are presented in section 4.2. The Eurelectric member states comprise all countries of the European Union plus Norway. The material demand of the global medium voltage and low voltage distribution system is described in section 4.3. The total global material stocks are shown in 4.4 with further elucidation regarding per capita material stocks, material stocks per land area, and material stocks in relation to electricity consumption. Eventually, a future outlook of material demand is given in section 4.5. The results of the global high voltage transmission infrastructure are based on the year 2019, and of the electricity infrastructure within the Eurelectric member states on the year 2011. The results of the medium and low voltage distribution system are based on data of the year 2011 (data regarding the line lengths) and 2019 (data regarding number of the population that has access to electricity and population density). The target year of the assessment is thus 2019 because most of the data is available. However, data sources are also combined that refer to different years in the period 2011-2019. In the following, the designation “Europe” comprises not only EU member states but also countries of the whole European continent (for detailed list see Appendix A).

4.1. Global High Voltage Transmission Infrastructure

This section features the results of material stocks in the global high voltage transmission infrastructure based on GIS data. Figure 4 shows the map of GIS data to get a better idea of what the data basis looks like (for further maps see Appendix H). Blue lines indicate alternative current (AC) lines and yellow lines direct current (DC) lines. Large differences can be observed between Europe / USA and especially Africa. DC lines were employed in the past and some parts are still in use. Recently, DC lines gain increasing significance because of its usage in high voltage UG cables (especially deep-sea cables) that are constructed as DC cables due to its cost-efficiency if the distance is longer than 30-40 km (Jorge and Hertwich, 2014). Nevertheless, the vast majority of lines and cables are AC. Table 8 and gives a comparative overview on the line lengths obtained from GIS data and lengths reported from official national energy statistics. GIS-based line lengths fit fairly well to national statistics and deviate between 7.9 % (Ireland) and 14.8 % (Austria) from official numbers.

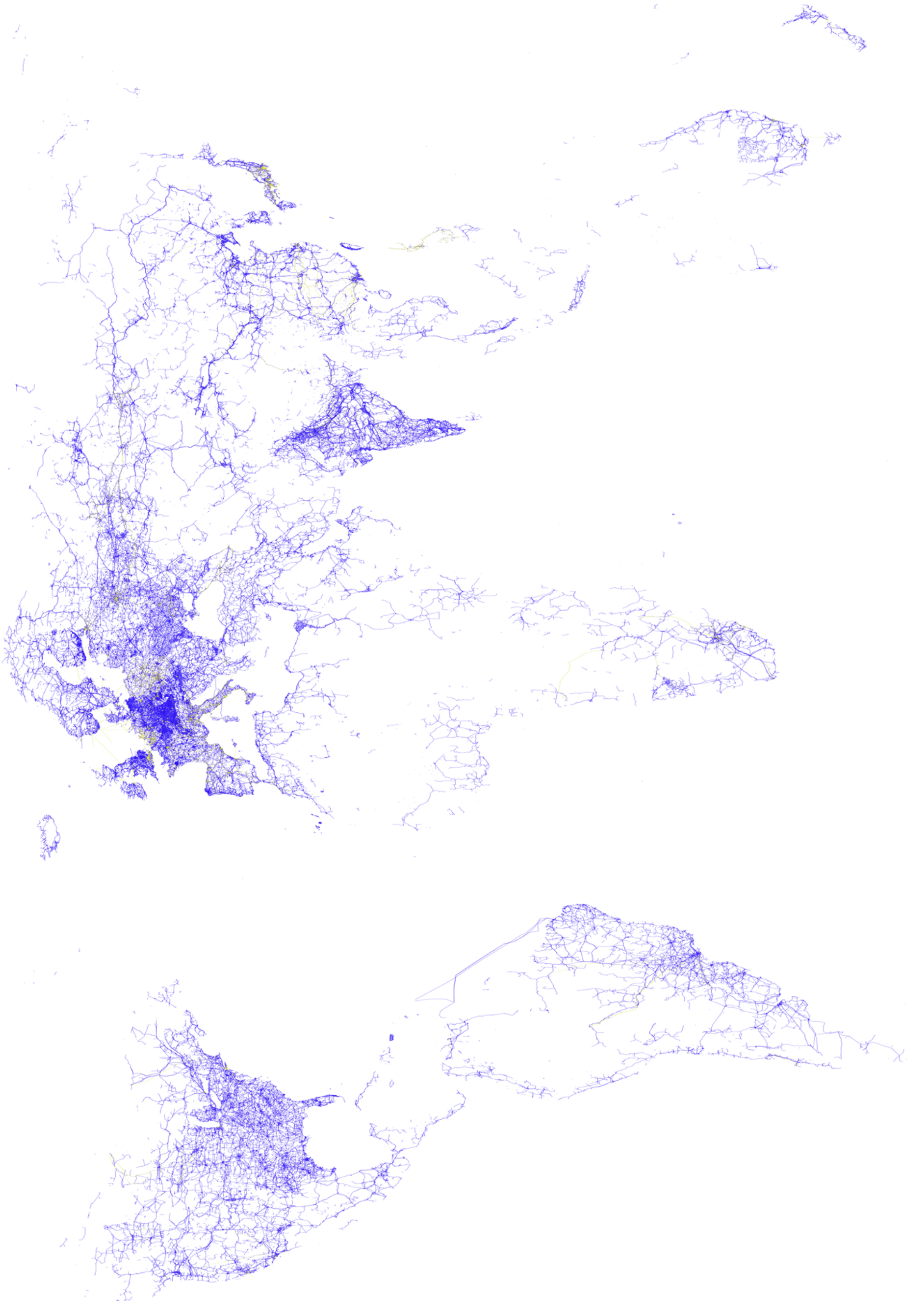


Figure 4: Global map of high voltage transmission lines and cables. Based on GIS data on the year 2019.

Table 8: Comparison of line lengths from GIS data and national statistics (in km).

	Ireland	Austria	USA	Japan
GIS data	7990	11207	436609	33648
National statistics	7407	9760	480000	38145
Deviation (%)	7.9	14.8	9.9	13.4

Fig. 5 demonstrates the line length obtained from GIS data in comparison to line length reported in official national statistics (data is shown in Table 8).

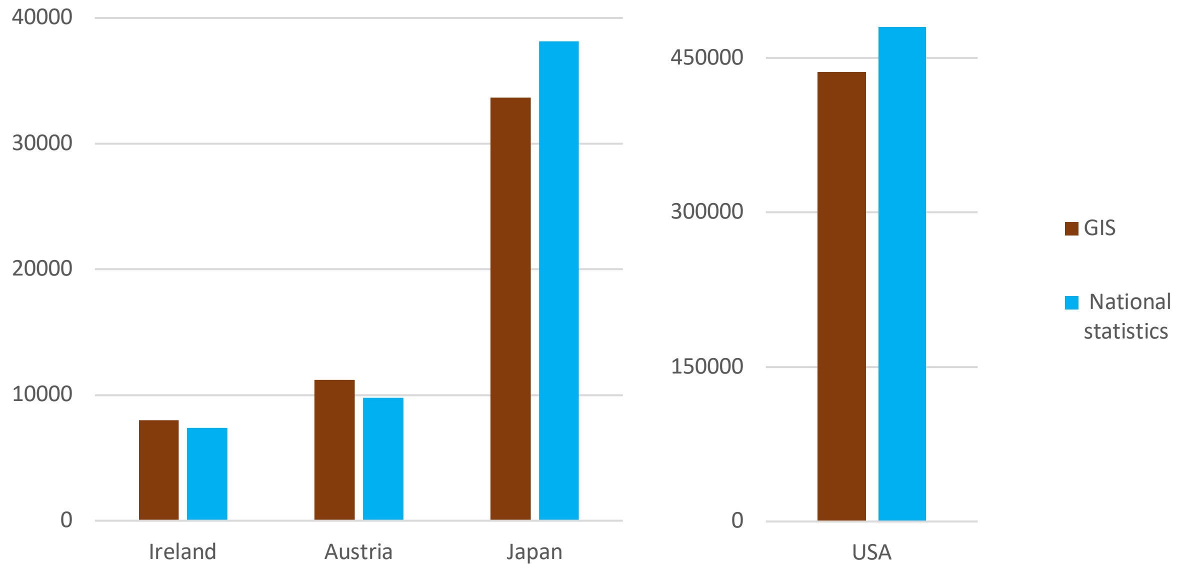


Figure 5: Comparative overview on the line lengths obtained from GIS data and selected national statistics based on the year 2019.

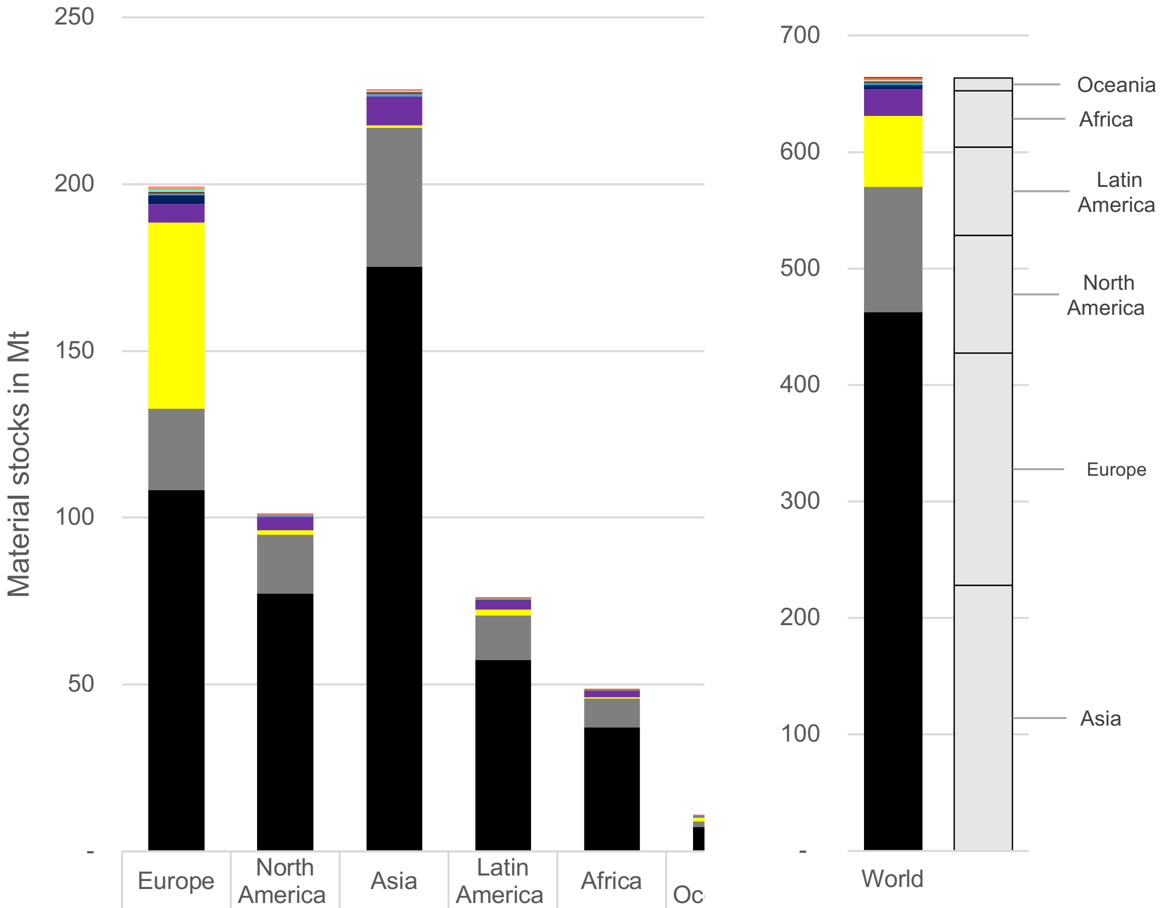
Table 9 shows the global transmission line length obtained from GIS data. In total, the global line length of OH and UG lines above 100 kV is roughly 2.7 million km whereas the vast majority stems from OH lines that account for around 98%. There is a general trend showing that the line length is inverse to its voltage level, meaning that the low voltage level contribute most to the total line length, followed by the medium voltage level and finally the high voltage level that makes up only little with respect to the total line length. North America shows a remarkable high line length at voltages at 500 kV or higher, which is three times higher for the levels between 500-600 kV and two times higher than 600-800 kV compared to Europe. This has implications on the material consumption of the high voltage transmission system.

Asia features the longest length with 953640 km, followed by Europe (720645 km), North America (497686 km), Latin America (312466 km), Africa (225257 km) and Oceania (54929 km). Europe has the longest line of UG cables amounting to 34804 km and are much higher than those of North America (815 km) which can be attributed to the sea cables connecting continental Europe to the UK and Norway as well as cables connecting Norway to the UK. It should be noted that the GIS data of UG cables are, except for Europe, probably not well mapped, which could be the primary reason for the low values in other continents. The only transmission lines of 1000 kV or above are located in China.

Table 9: Line length of the high voltage transmission overhead (OH) lines and underground (UG) cables (in km). Values are derived from GIS data based on the year 2019.

		Voltage level (kV)							
		>800	600-800	500-600	400-600	300-400	200-300	100-200	Total
Europe	OH	-	8424	17078	89273	82215	136602	352248	685841
	UG	-	-	950	21317	1992	3396	7149	34804
	Total	-	8424	18028	110589	84208	139997	359398	720645
North America	OH	-	16375	57758	6936	83831	148504	183467	496871
	UG	-	-	71	-	172	63	509	815
	Total	-	16375	57829	6936	84003	148567	183976	497686
Asia	OH	2297	60997	135735	126718	22369	291274	313741	953131
	UG	-	-	52	154	5	91	206	508
	Total	2297	60997	135787	126873	22374	291365	313947	953640
Africa	OH	-	2614	11976	35901	22453	87555	64558	225057
	UG	-	-	-	106	2	4	87	200
	Total	-	2614	11976	36007	22455	87559	64644	225257
Latin America	OH	-	7034	74711	24436	10714	95847	98721	311464
	UG	-	-	-	-	22	85	894	1001
	Total	-	7034	74711	24436	10737	95932	99615	312466
Oceania	OH	-	-	1723	66	7257	20527	24628	54202
	UG	-	-	0	300	38	176	213	727
	Total	-	-	1723	367	7295	20703	24841	54929
World	OH	2297	95444	298981	283330	228840	780310	1037364	2726565
	UG	-	-	1074	21878	2233	3815	9058	38056
	Total	2297	95444	300055	305208	231073	784125	1046422	2764622

Fig. 6 illustrates total material stocks of the global high voltage transmission infrastructure. In sum, material stocks amount to 663 million tonnes (Mt). Asia has the largest amounts of materials with about 228 Mt accounting for 34%, followed by Europe with 199 Mt (30%), North America with 101 Mt (15%), Latin America with 76 Mt (11%), Africa with 48 Mt (7%), and Oceania with 11 Mt (1%).



	Europe	North America	Asia	Latin America	Africa	Oc
Plastics	0.1	0.0	0.0	0.0	0.0	
Paper	0.1	0.0	0.0	0.0	0.0	[illegible]
Copper	0.4	0.0	0.0	0.0	0.0	0.0
Lead	0.5	0.0	0.0	0.0	0.0	0.0
Zinc	0.3	0.2	0.6	0.2	0.1	0.0
Mineral oil	0.5	0.2	0.5	0.2	0.1	0.0
Hard glass	0.5	0.3	0.8	0.3	0.2	0.0
Asphalt	2.6	0.1	0.0	0.1	0.0	0.1
Aluminum	5.6	4.0	8.7	2.8	1.9	0.4
Sand	55.7	1.3	0.8	1.6	0.3	1.2
Steel	24.4	17.6	41.6	13.6	8.6	1.6
Concrete	108.3	77.3	175.2	57.2	37.2	7.3

Figure 6: Material stocks in the high voltage transmission system based on the year 2019 (in Mt).

The bulk of material stocks comes from the steel-reinforced concrete foundations and steel towers, but also from sand for the cable ducts. The material demand for UG high voltage cables per km is substantially higher by a factor of 4.6 – 10.5 (compared to 400 and 150 kV OH lines). This arises predominantly from the use of sand in UG cables, which accounts to 1600 tonnes per km of cable length. Despite the much lower length of global high voltage UG cables, the high material intensity of sand makes the amount significant and accounts to almost 10% of total material stocks.

The material that is incorporated only in the lines and cables (no fundaments, towers and ducts) reaches 40 Mt and thus only accounts for 6% of the total stocks. As can be seen in Fig. 7, the largest quantity arises from the aluminum conductors that are steel-reinforced. The total amount of installed aluminum is 23 Mt. The steel stocks in conductors, earth conductors and insulation account to 12 Mt. The remaining stocks mainly come from line insulation material such as hard glass (2.1 Mt), mineral oil (1.5 Mt), and plastics (0.1 Mt). Copper, lead and asphalt is incorporated in the high voltage UG cables and makes up 0.4 Mt, 0.5 and 0.03 Mt respectively.

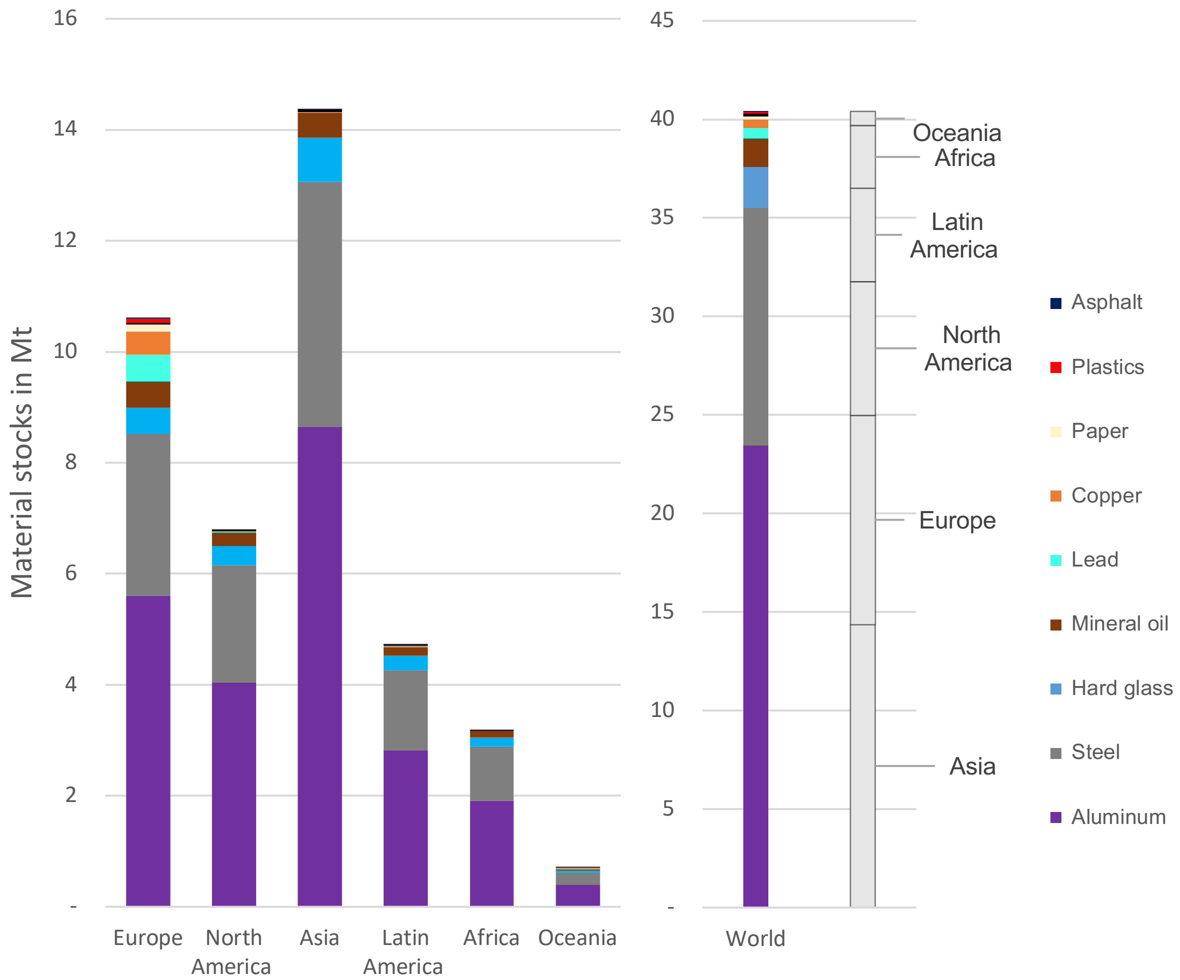


Figure 7: Material stocks of high voltage overhead lines and underground cables without fundament, towers, and cable ducts based on the year 2019 (in Mt).

4.2. Electricity infrastructure in Eurelectric Member States

This section shows material stocks within Eurelectric member states. “Eurelectric” is the Industry association of the European electricity industry and its member states include every member state of the EU plus Norway (data is based on Eurelectric (2011)). The lengths are separated to their voltage level, as well as into OH and UG, as can be seen in Table 10. The total line length in Eurelectric member states amounts to roughly 9.9 million km. As stated above, there is an inverse relationship between the line length and the voltage level, meaning that the bulk of line length comes from the medium- and low voltage power lines. 60% of the line length stems from low voltage, 37% from medium voltage, and 3% from high voltage systems.

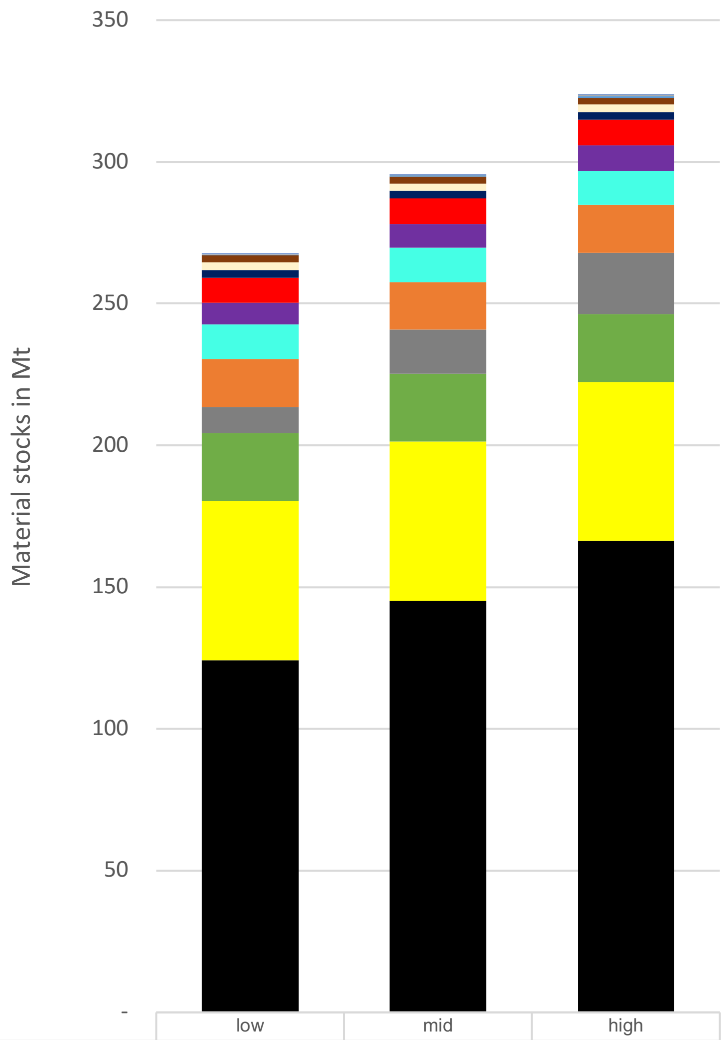
There are substantial differences regarding the share of the length of OH lines and UG cables on their respective voltage level. In high voltage levels, the share of UG lines is only 11%, whereas this share increases according to lower voltage levels. Therefore, the share of UG lines in medium voltage levels is 41% and in low voltage levels 55%. This is owing to the fact, that medium- and low voltage distribution lines are predominantly concentrated in urban areas where visual impacts are undesirable. Germany, France, and Italy have the most extensive transmission and distribution grid, whereas Belgium, the Netherlands and Germany show the highest line density (km of lines per km^2). The line density corresponds well to the respective population density. This implies that the population and the area of a nation largely determines the power line length.

The discrepancy between the share of UG cables in the high voltage transmission system in the Eurelectric member states and the GIS-data presumably stems from the fact that transmission cables may not be well-recorded in the GIS data. Other reasons could be that there is no need for transmission cables in North America due to its topography. Because of the absence of remote islands that are connected to the grid (compared to Europe e.g. UK, Scandinavia), North American regions are not divided by oceans that require the construction of transmission deep-sea cables. The lack of UG cables in Asia may be explained by its high construction costs and the lower affordability in Asian countries. The same could hold for Africa.

Table 10: Power lines in Eurelectric member states according to Eurelectric (2011) (in km).

		High voltage			Medium voltage			Low voltage		
Country	Total	Total	OH	UG	Total	OH	UG	Total	OH	UG
AT	235600	9760	9200	560	65550	29250	36300	160300	37600	122700
BE	193165	-	-	-	72522	7021	65501	120644	52164	68480
BG	153916	114	73	41	64452	49651	14801	89350	63533	25817
CY	22428	-	-	-	8787	5482	3305	13640	9206	4434
CZ	221441	12258	12245	13	71713	58734	12979	137470	65764	71706
DE	1772696	113887	106869	7018	506671	122226	384445	1152138	143516	1008622
DK	171819	1743	1364	379	73983	8629	65354	96093	3961	92132
EE	60000	-	-	-	26000	20000	6000	34000	26000	8000
ES	695427	31380	30363	1017	280987	203225	77762	383202	241735	141467
FI	382740	6622	6438	184	138153	121153	17000	237966	148758	89208
FR	1293466	-	-	-	608053	356263	251790	685413	419060	266353
GR	229877	777	569	208	107691	96793	9915	121407	107837	13570
HU	161954	7873	7755	118	66816	53887	12929	87266	64039	33227
IE	167528	538	402	136	97790	87866	9924	69200	57100	12100
IT	1105216	-	-	-	342600	207247	135353	762616	510301	252315
LT	123749	-	-	-	54017	43362	10655	69732	56848	12884
LU	8477	-	-	-	3159	1115	2044	5318	319	4999
LV	93764	-	-	-	34964	29434	5530	58800	40640	18160
NL	252634	-	-	-	-	-	-	146666	-	-
PL	774141	32671	32486	185	305492	234732	70760	435978	291671	144307
PT	222627	-	-	-	83256	66725	16531	139371	106744	32627
RO	89944	6584	6332	252	34666	22645	12021	48695	28589	20106
SE	528606	-	-	-	-	-	-	306019	69868	236151
SI	63120	811	810	10	16854	12189	4655	45456	24655	20801
SK	91353	6743	-	-	32361	-	-	52250	-	-
UK	837156	75440	50462	24978	352841	193102	159739	408875	70276	338599
NO	128591	11062	-	-	18687	-	-	98842	-	-
Total	**9952845**	**307200**	**265368**	**35099**	**3555204**	**2030731**	**1385161**	**5867865**	**2491526**	**3038746**

As can be seen in Fig. 8, total material stocks that are incorporated in the transmission and distribution system lie between 267 and 324 Mt with a medium value of 296 Mt. Again, the majority stems from concrete foundations of transmission systems and timber from wood poles in distribution systems. The range of “low”-, “mid”-, and “high” arises from the missing data about the different voltage levels in the highest voltage transmission lines. Since there are differences in the material intensities of power lines of 150 kV and 400 kV, a “low”-, “mid”-, and “high” estimate gives the range of material stocks within the Eurelectric member states. The estimate “low” assumes a transmission system that only consists of 150 kV lines, “high” corresponds to 400 kV lines only, and “mid” denotes the average of both.



	low	mid	high
Resins	0.1	0.1	0.1
Zinc	0.1	0.2	0.4
Porcelain/hard glass	0.3	0.4	0.5
Mineral oil	2.5	2.5	2.5
Paper	2.6	2.6	2.6
Asphalt	2.7	2.7	2.7
Plastics	9.0	9.0	9.0
Aluminum	7.7	8.4	9.0
Lead	12.1	12.1	12.1
Copper	16.8	16.8	16.8
Steel	9.3	15.4	21.6
Timber	23.9	23.9	23.9
Sand	56.2	56.2	56.2
Concrete	124.3	145.3	166.3

Figure 8: Material stocks of the total electricity infrastructure within the Eurelectric member states based on the year 2011 (in Mt).

The material stocks without foundations, steel lattice towers and wood poles, and cable ducts are shown in Fig. 9. Copper is the most relevant material. This is attributed to the fact, that the low- and medium distribution system, where copper is one of the main constituents, has a far greater length. Another major material is lead. The high mass of lead that is used for the cable sheath can also be explained by its high density and thus its high mass per volume. The density of lead is around one third higher than the density of copper and over four times higher than the density of aluminum (Wachter, 1989). Aluminum with 8 Mt ranks fourth due to its employment in the transmission and medium voltage distribution system, which is shorter in its length. Moreover, aluminum is much lighter in its weight (as explained above) and has much less impact on the total mass.

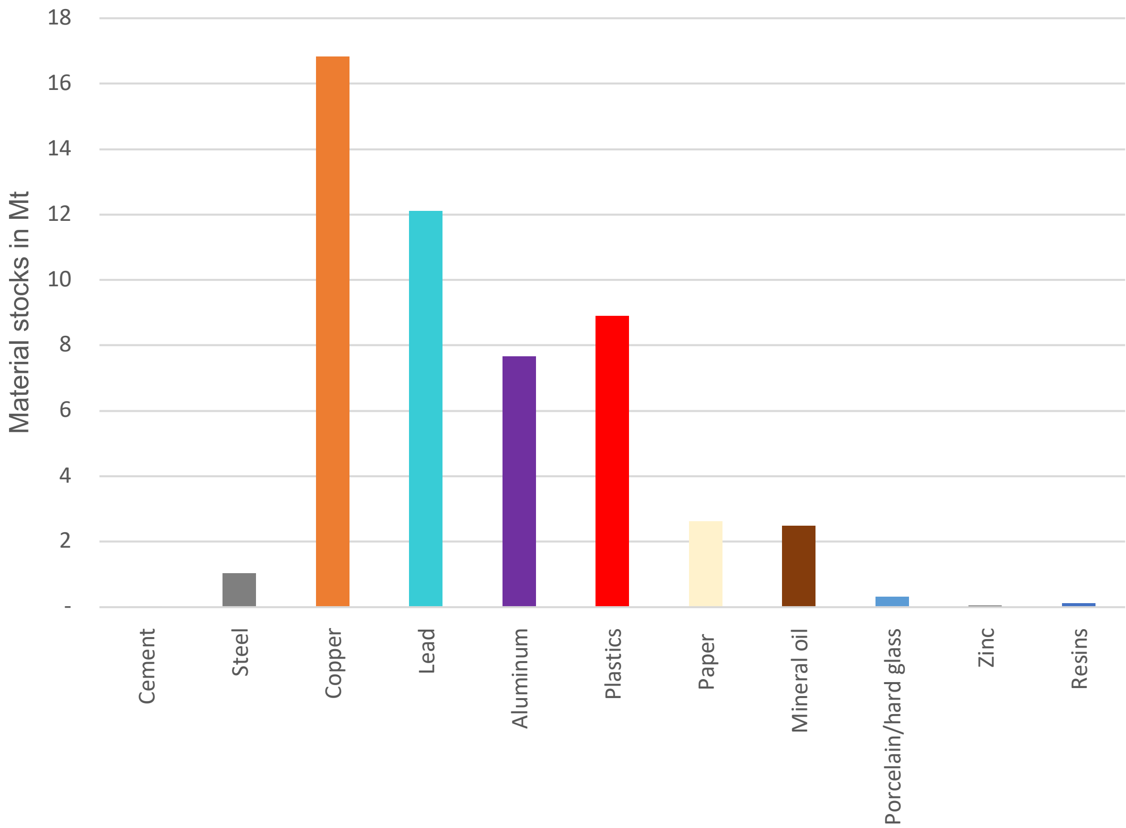


Figure 9: Material stocks in the Eurelectric member states without foundations, towers, and cable ducts based on the year 2011 (in Mt). Low amounts of cement and zinc are employed in high voltage overhead lines as insulators and as coating agent respectively.

Figure 10 illustrates the proportions of the material stocks of OH and UG in their respective voltage levels. The values for the high voltage levels represent the average estimate of the material stocks in the high voltage OH lines and UG cables. "Others" refers to a summary term for the materials copper, aluminum, lead, steel, zinc, plastics, paper, mineral oil, porcelain / hard glass, cement, and resins. The high voltage transmission system therefore accounts for the largest amount of material stocks with 133 ± 28 Mt, followed by the low voltage distribution system with 95 Mt. The medium voltage distribution systems add up to 67 Mt.

Additionally, one can witness the relationship of material stocks of the OH and UG system with respect to the voltage level. In the distribution system, a significant part of material stocks stems from UG cables, predominantly from concrete, copper, and lead. In the transmission system the amount of material stocks is largely driven by the steel-reinforced concrete foundations (41% for concrete) and steel towers for OH lines (9%). This reason is twofold, namely (a), the fact that the transmission system consists primarily of OH lines, and (b), the higher material requirements for concrete foundations compared to concrete cable ducts as a well as for steel for the masts. Furthermore, it becomes visible that sand represents a major part of the total stocks, accounting to 42% of total material stocks in the transmission system.

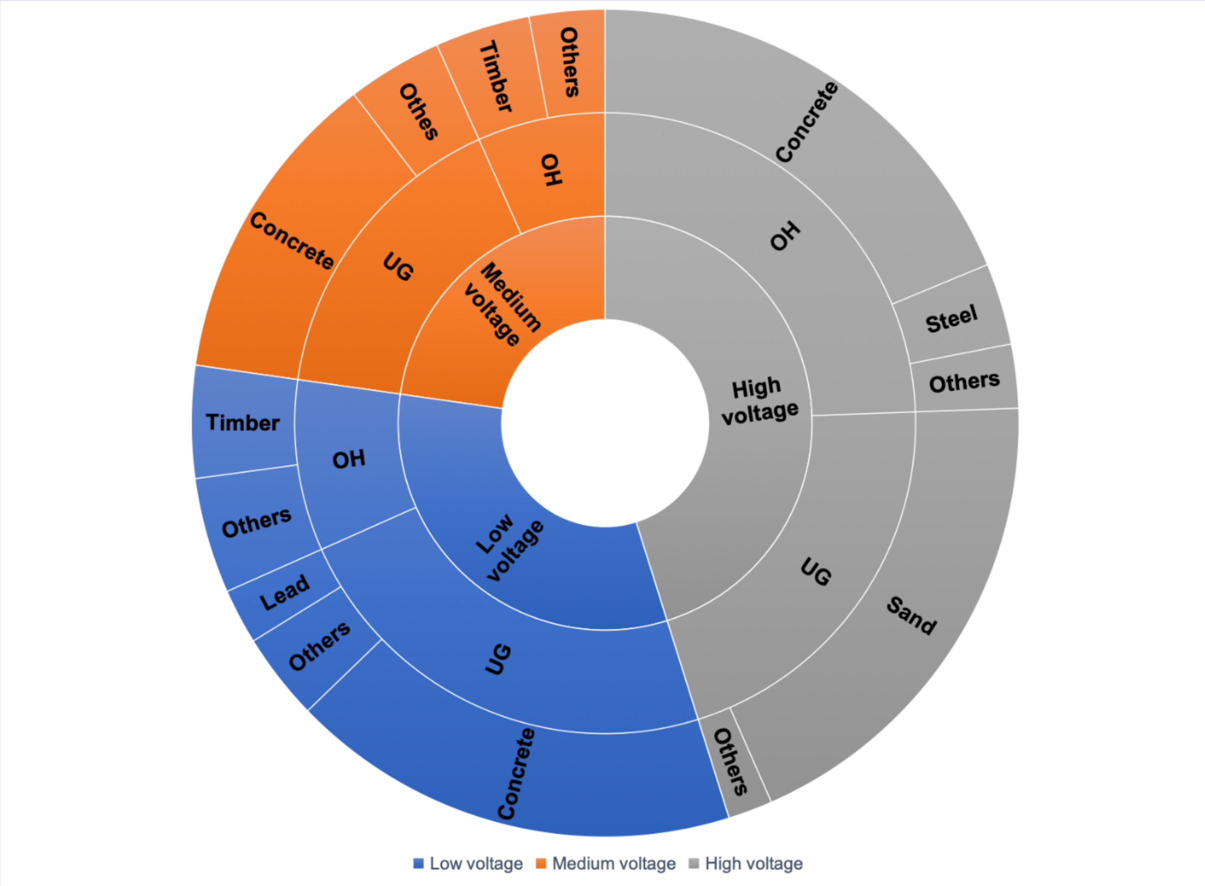


Figure 10: Relative proportions of material stocks by voltage level and overhead and underground based on the year 2011.

The composition of materials in the distribution system is similar. Concrete for the cable ducts is the major contributor to the total material stocks and amounts to 52 Mt (55%) and 37 Mt (54%) in the low-, and medium voltage system respectively. In addition, timber for the wood poles represents the second-largest material stock, followed by lead (8%), copper (5%), and plastics (4%) for the low voltage system and copper (7%), plastics (4%), aluminum (3%), and steel (3%) for the medium voltage system. The relative share of copper in the medium voltage system is higher, due to the higher copper requirements in lines and cables of higher voltage levels.

4.3. Global Distribution Infrastructure

This section presents the material stocks of the global distribution infrastructure, which is the sum of the low voltage (< 1kV) and medium voltage (1-100 kV) system. The line lengths of the global distribution system were estimated through multiple regression analysis. This was done because the GIS data showed significant deviation from official national statistics at voltage levels below 100 kV. The general trend was that the lower the voltage level, the higher was the difference between GIS data and national statistics. Therefore, a regression model based on official data of Eurelectric member states (see also Eurelectric (2011)) was developed to estimate the line lengths of the distribution system for countries of the rest of the world (for further explanation see section 3.3.1). The explanatory variables "popaccesselec", representing the number of the population that has access to electricity, and "popdensity, referring to the population density of a country, are based on data of the year 2019.

Table 11 provides the descriptive statistics from multiple regression analysis. The R^2 yields 0.99 and the adjusted R^2 0.97. The p-value of the parameter "popaccesselec" for the number of populations that have access to electricity is highly significant with $4*10^{-4}$ in contrast to the parameter "popdensity" for the population density. The coefficients of both explanatory variables are positive, meaning that the population as well as the population density have a positive correlation with the line length. Countries with a higher population and population density have therefore more power lines.

Table 11: Summary statistics of multiple regression analysis.

Multiple R	0.99							
R^2	0.97							
Adjust. R^2	0.97							
Standard Error	4267							
N	26							
	Coeff.	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95%	Upper 95%
Intercept	9840	129621	0.76	0.46	-169741	366543	-169741	3665
Popdensity	406	769	0.53	0.60	-1186	1998	-1186	1998
Popaccesselec	0.01	0.00	23	0.00	0.01	0.01	0.01	0.01

Fig. 11 demonstrates high voltage line lengths obtained from multiple regression analysis in comparison to lengths from GIS data. Although the regression model was used to estimate lengths for the low-, and medium voltage system only (because GIS data was used to calculate lengths of the high voltage system), this figure was chosen to show that GIS-based lengths are within the low-, and high estimate of the regression model. As has been shown in section 4.1, line lengths from GIS data fit rather well to selected official national energy statistics. Consequently, if GIS data fit to national statistics, and lengths from regression analysis fit to

GIS data, one can infer that lengths from regression analysis may fit relatively well to national statistics.

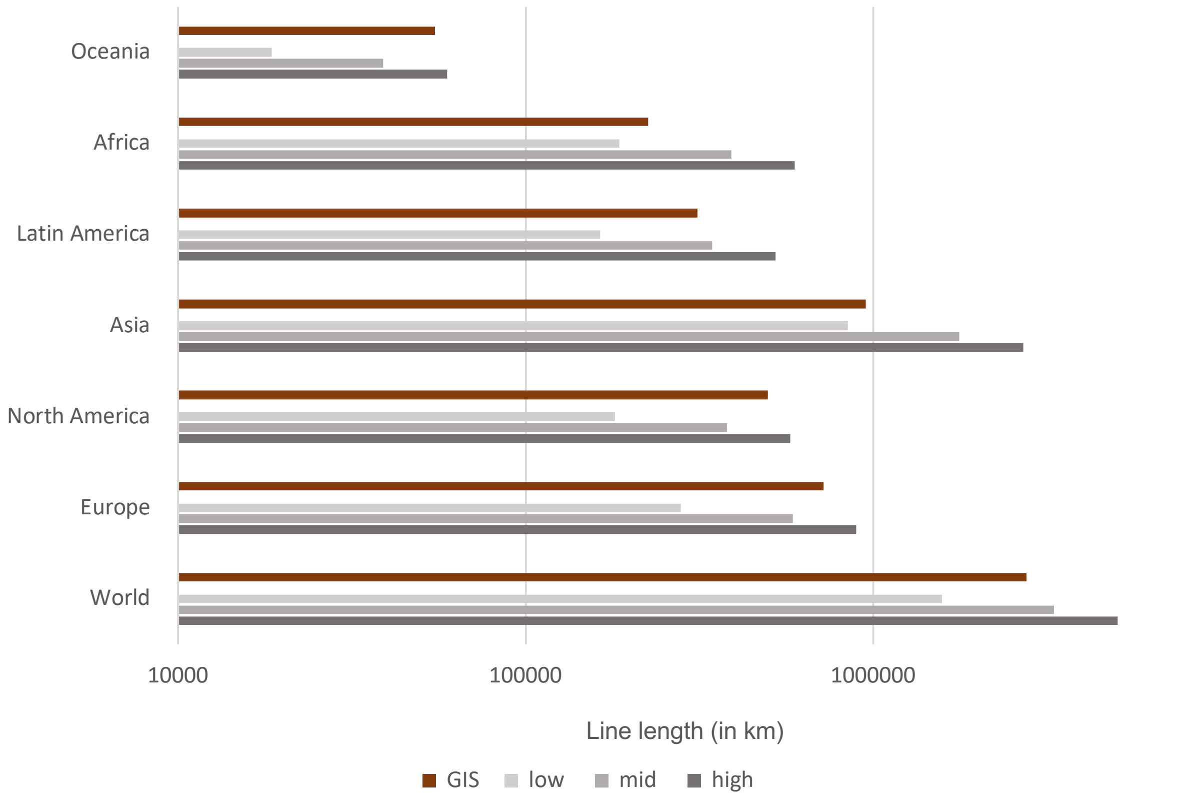


Figure 11: Comparative overview on the line lengths obtained from multiple regression analysis and GIS data (in km). Horizontal axis is on logarithmic scale.

Table 12 shows the results of the statistical estimation regarding the global distribution line length. Based on data from Eurelectric (2011), it provides information about the proportion of OH and UG line lengths in medium- and low voltage levels (high voltage level is not shown since it has already been examined above through GIS data). The first table section shows the proportion in each country of Eurelectric member states in percent. The second table section shows the results from the descriptive statistics. Based on the standard deviation, the standard error of the mean (SEM), and the degrees of freedom (df), the critical t-value is calculated, hence the 95% confidence interval. The third table section exhibits the percentage proportion of lines, divided into low-, mid-, and high estimate, based on the mean and the 95% confidence interval. The final table section gives information regarding the line lengths of OH and UG lines in the medium- and low voltage levels, based on multiplication of the total line length obtained from the multiple regression and the respective percentage share.

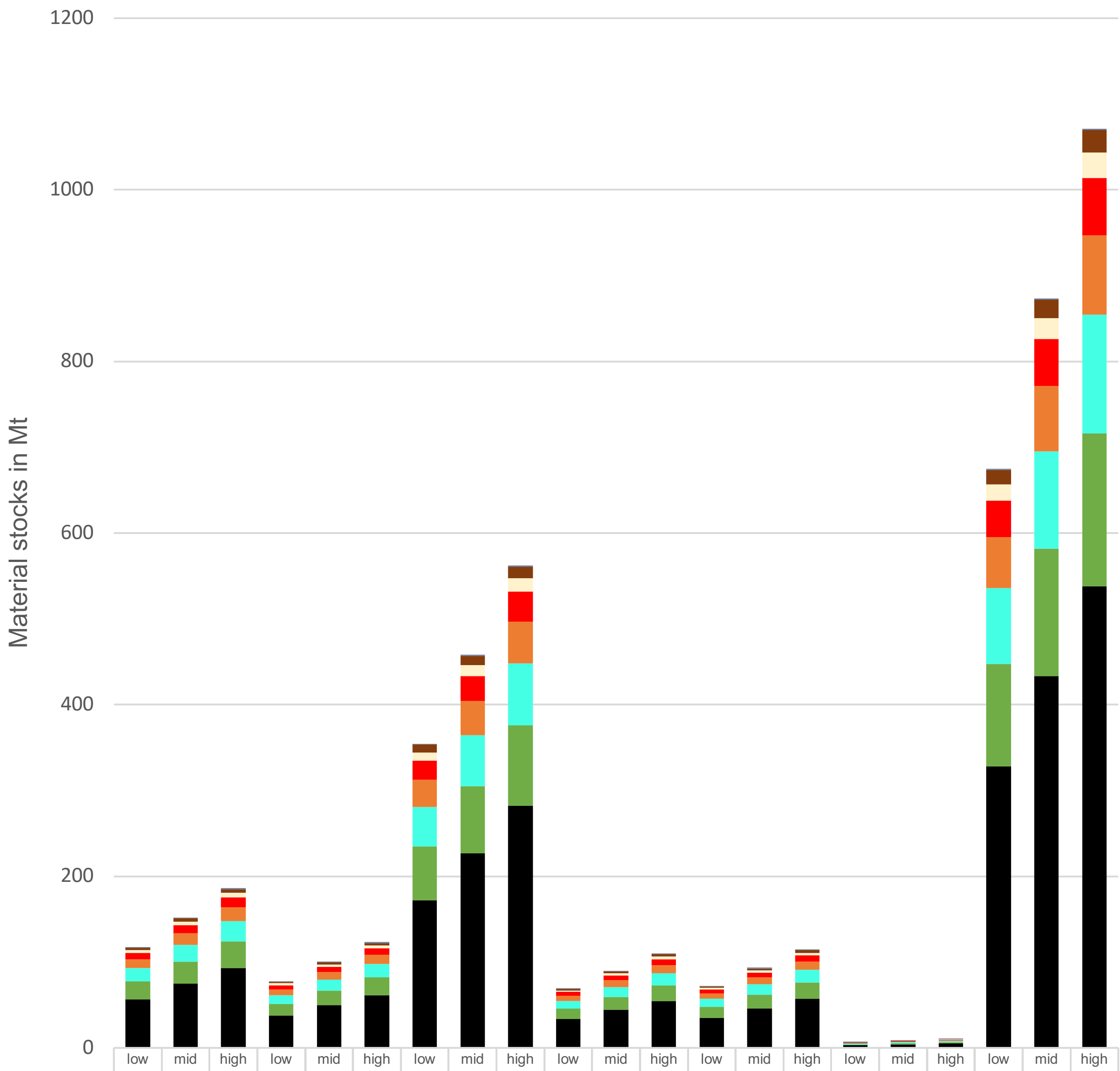
The low voltage distribution network is not only the longest, but also features the largest portion of material stocks in the electricity infrastructure (contrary to the Eurelectric member states where the high voltage transmission system ranks first, see Fig. 10 above). Low voltage lines take the largest part with OH lines of 29.9 million km and UG of 26.5 million km, amounting to a total length of 56.3 million km in the low voltage level. Considering the medium voltage lines, the total length is 37.3 million km, whereas the OH length is 24.4 million km, and the UG length is 12.9 million km. The total line length arises from the summation of each total line length in each country worldwide and amounts to about 95.6 million km (see Appendix B).

Overall material stocks in the low voltage system amount to 872 ± 198 Mt (see Fig. 12). Here, the “low”-, “mid”-, and “high” estimate arise from the lower and upper limit from the 95% confidence interval, as shown in Table 12 (in contrast to the values in the Eurelectric member states, see above in section 0). Concrete from cable ducts in UG cables and wood poles of masts in OH lines contain the majority of material stocks with 433 ± 105 Mt and 149 ± 30 Mt respectively. This corresponds to around 62% with respect to total global stocks. However, this share is somewhat lower than in high voltage lines. This is reasonable, because the towers and their foundations in high voltage lines entail considerably greater amounts of concrete and steel, due to the much higher requirements for stability and durability.

Table 12: Calculation of the low voltage and medium voltage distribution line length. The first table section shows the proportion in each country of Eurelectric member states in percent. The second table section shows the results from the descriptive statistics. The third table section shows the percentage proportion of lines, divided into low-, mid-, and high estimate, based on the mean and the 95% confidence interval. The final table section provides the line lengths of overhead (OH) and underground (UG) lines in the medium-, and low voltage levels through multiplication of the total line length obtained from the regression model and the respective percentage share. Data is based on Eurelectric (2011).

	Medium voltage			Low voltage		
	Total	OH	UG	Total	OH	UG
Share on total line length (%)						
AT	0.28	0.12	0.15	0.68	0.16	0.52
BE	0.38	0.04	0.34	0.62	0.27	0.35
BG	0.42	0.32	0.10	0.58	0.41	0.17
CY	0.39	0.24	0.15	0.61	0.41	0.20
CZ	0.32	0.27	0.06	0.62	0.30	0.32
DE	0.29	0.07	0.22	0.65	0.08	0.57
DK	0.43	0.05	0.38	0.56	0.02	0.54
EE	0.43	0.33	0.10	0.57	0.43	0.13
ES	0.40	0.29	0.11	0.55	0.35	0.20
FI	0.36	0.32	0.04	0.62	0.39	0.23
FR	0.47	0.28	0.19	0.53	0.32	0.21
GR	0.47	0.42	0.04	0.53	0.47	0.06
HU	0.41	0.33	0.08	0.54	0.40	0.21
IE	0.58	0.52	0.06	0.41	0.34	0.07
IT	0.31	0.19	0.12	0.69	0.46	0.23
LT	0.44	0.35	0.09	0.56	0.46	0.10
LU	0.37	0.13	0.24	0.63	0.04	0.59

	Medium voltage			Low voltage		
	Total	OH	UG	Total	OH	UG
LV	0.37	0.31	0.06	0.63	0.43	0.19
NL	-	-	-	0.58	-	-
PL	0.39	0.30	0.09	0.56	0.38	0.19
PT	0.37	0.30	0.07	0.63	0.48	0.15
RO	0.39	0.25	0.13	0.54	0.32	0.22
SE	-	-	-	0.58	0.13	0.45
SI	0.27	0.19	0.07	0.72	0.39	0.33
SK	0.35	-	-	0.57	-	-
UK	0.42	0.23	0.19	0.49	0.08	0.40
NO	0.15	-	-	0.77	-	-
Statistics						
Mean	0.39	0.26	0.13	0.59	0.31	0.28
SD	0.07	0.12	0.09	0.07	0.14	0.16
SEM	0.01	0.02	0.02	0.01	0.03	0.03
N	23	23	23	23	24	24
df	22	22	22	22	23	23
t(crit)	2.08	2.08	2.08	2.08	2.07	2.07
95% confidence interval	0.03	0.05	0.04	0.03	0.06	0.07
Share on line length (%)						
low	0.36	0.20	0.10	0.56	0.25	0.21
mid	0.39	0.26	0.13	0.59	0.31	0.28
high	0.42	0.31	0.17	0.62	0.38	0.34
Line length (km)						
low	34354127	19510851	9135009	53483736	24048090	20038668
mid	37270434	24394254	12876181	56286404	29974428	26454276
high	40186741	29277656	16617352	59089071	35900765	32869884



	Europe			North America			Asia			Latin America			Africa			Oceania			World		
	low	mid	high	low	mid	high	low	mid	high	low	mid	high	low	mid	high	low	mid	high	low	mid	high
Steel	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
Resins	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.3	0.4	0.0	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.5	0.6	0.8
Mineral oil	2.9	3.7	4.5	1.9	2.5	3.0	8.8	11.3	13.8	1.7	2.2	2.7	1.8	2.3	2.8	0.2	0.2	0.2	16.8	21.6	26.3
Paper	3.3	4.2	5.1	2.2	2.8	3.4	9.9	12.7	15.5	1.9	2.5	3.0	2.0	2.6	3.1	0.2	0.2	0.3	19.0	24.3	29.6
Plastics	7.4	9.4	11.5	4.9	6.2	7.6	22.3	28.6	34.9	4.3	5.6	6.8	4.5	5.8	7.1	0.4	0.5	0.6	42.6	54.5	66.5
Copper	10.3	13.2	16.1	6.8	8.7	10.6	31.2	40.0	48.7	6.1	7.8	9.5	6.3	8.1	9.9	0.6	0.7	0.9	59.6	76.2	92.9
Lead	15.3	19.6	23.9	10.1	13.0	15.8	46.4	59.4	72.3	9.0	11.6	14.1	9.4	12.0	14.7	0.8	1.1	1.3	88.4	113.2	138.0
Timber	20.7	25.8	30.9	13.7	17.0	20.4	62.6	78.1	93.5	12.2	15.2	18.2	12.7	15.8	19.0	1.1	1.4	1.7	119.5	148.9	178.4
Concrete	56.8	75.0	93.1	37.5	49.6	61.6	172.0	227.1	282.1	33.5	44.2	54.9	34.9	46.1	57.2	3.1	4.1	5.1	328.0	433.0	538.1

Figure 12: Material stocks in the global low voltage distribution system based on the year 2019 (in Mt).

The material stocks of the global low voltage distribution system regarding the OH lines and UG cables (without foundation, ducts, and masts) are demonstrated in Fig. 13. The copper stock amounts to 40 ± 8 Mt in the OH and to 35 ± 8 Mt in the UG system, representing the second-highest copper stocks in the electricity infrastructure. Lead makes up a major share with 60 ± 12 Mt in the OH and 53 ± 12 Mt in the UG system. Other important material stocks are paper and mineral oil. Altogether, material stocks are 154 ± 30 Mt for the OH and 136 ± 33 Mt for the UG system, that sums up to 289 ± 63 Mt in total.

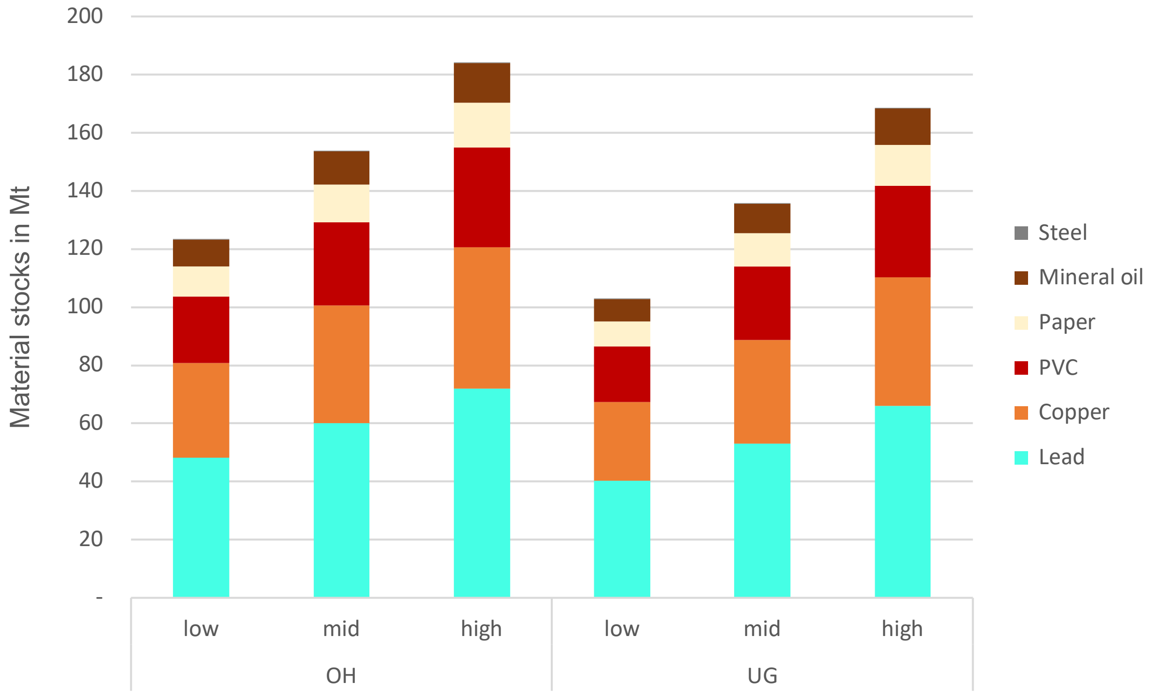
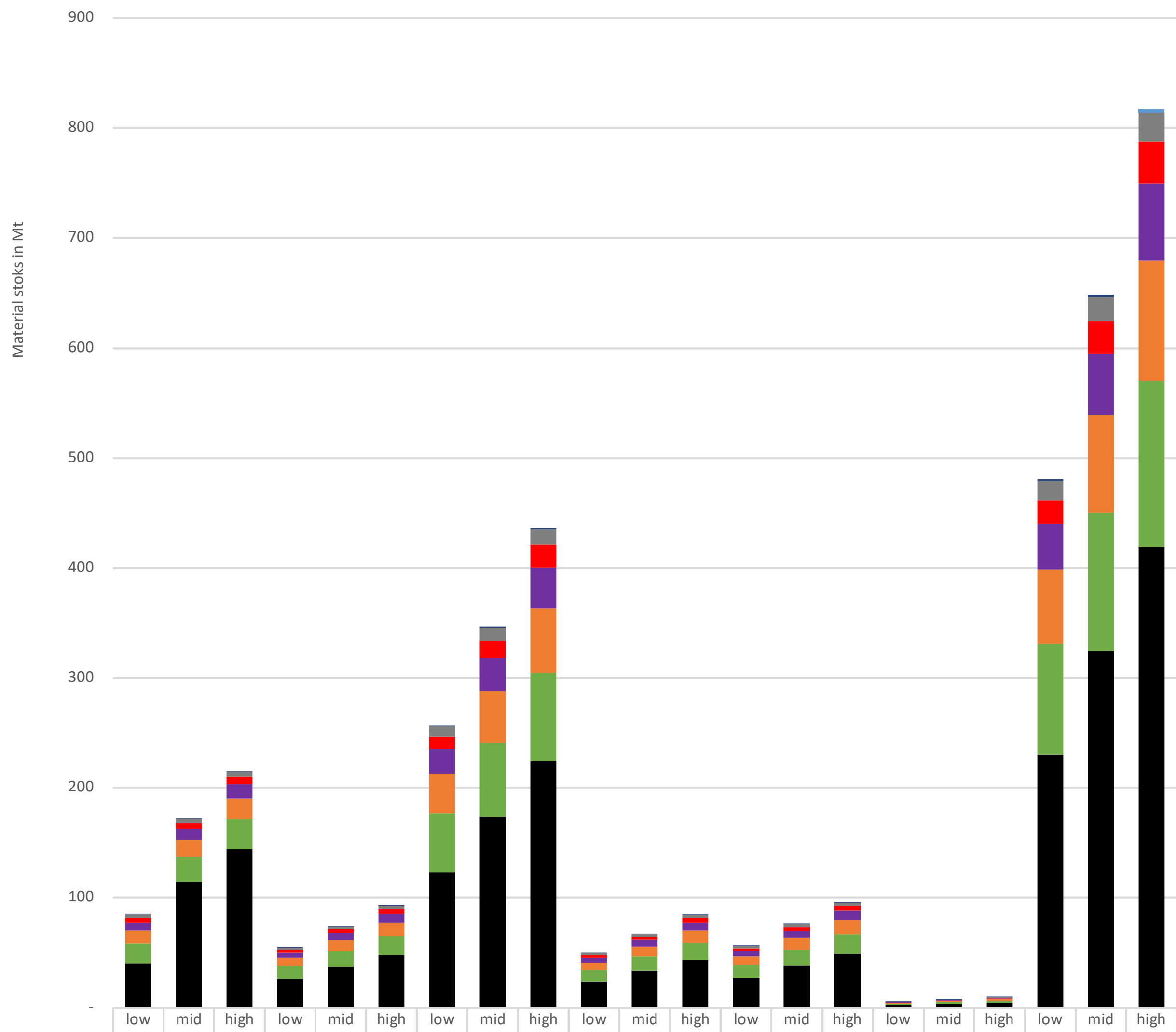


Figure 13: Material stocks in global low voltage overhead (OH) lines and underground (UG) cables without foundation, towers, and ducts based on the year 2019 (in Mt).

The material stocks of the global medium voltage OH and UG system are shown in Fig. 14. Total material stocks in the medium voltage distribution system account to 648 ± 168 Mt. Unsurprisingly, Asia contributes the most with 340 ± 88 Mt, followed by Europe (168 ± 42 Mt), North America (74 ± 19 Mt), Africa (69 ± 18 Mt), Latin America (66 ± 17 Mt) and Oceania (6 ± 1.6 Mt). The copper and aluminum stocks in the medium voltage distribution system are the most significant within the entire electricity infrastructure and amount to 89 ± 21 Mt and 56 ± 14 Mt respectively. Despite higher timber requirements per kilometer, timber stocks of 126 ± 25 Mt are slightly lower compared to the low voltage system. This is because the low voltage system is longer than the medium voltage system.



	Europe low	Europe mid	Europe high	North America low	North America mid	North America high	Asia low	Asia mid	Asia high	Latin America low	Latin America mid	Latin America high	Africa low	Africa mid	Africa high	Oceania low	Oceania mid	Oceania high	World low	World mid	World high
Porcelain	0.3	0.4	0.5	0.2	0.3	0.3	0.9	1.2	1.4	0.2	0.2	0.3	0.2	0.3	0.3	0.0	0.0	0.0	1.7	2.2	2.7
Steel	3.1	3.9	4.6	2.0	2.5	3.0	9.3	11.6	14.0	1.8	2.3	2.7	2.0	2.6	3.1	0.2	0.3	0.3	17.4	21.8	26.2
Plastics	3.8	5.3	6.8	2.4	3.4	4.4	11.3	15.9	20.5	2.2	3.1	4.0	2.5	3.5	4.5	0.2	0.3	0.5	21.2	29.8	38.3
Aluminium	7.4	9.9	12.4	4.8	6.4	8.0	22.2	29.8	37.4	4.3	5.8	7.3	4.9	6.6	8.2	0.5	0.7	0.8	41.6	55.8	70.0
Copper	12.0	15.7	19.4	7.8	10.1	12.5	36.2	47.3	58.5	7.0	9.2	11.4	8.0	10.4	12.9	0.8	1.0	1.3	67.7	88.5	109.4
Timber	17.8	22.3	26.7	11.5	14.4	17.3	53.8	67.2	80.7	10.4	13.1	15.7	11.8	14.8	17.8	1.2	1.5	1.8	100.6	125.7	150.9
Concrete	40.8	114.9	144.7	26.4	37.2	48.0	123.2	173.6	224.0	23.9	33.7	43.5	27.1	38.2	49.3	2.7	3.8	4.9	230.4	324.8	419.1

Figure 14: Material stocks of the global medium voltage distribution system based on the year 2019 (in Mt).

Fig. 15 illustrates the material stocks without foundation, masts, and cable ducts. The amount of total stocks in the OH and UG system is similar; however, the UG system has a larger variety. This can be explained by the larger standard deviation of the length of UG cables in the medium voltage system within the Eurelectric member states, which was derived from the data of Eurelectric (2011). Considering the stocks without foundations, towers, and ducts, the OH system makes up 100 ± 20 Mt, whereas the mass of UG system is on average marginally lower with 98 ± 28 Mt. Besides copper and aluminum, there is a noteworthy plastic stock in the UG system which stems from polyvinvyl chloride (PVC) and Ethylene-propylene rubber

(EPR) for the sheath and jacketing of the cable. Porcelain, silicon rubber and resins are rather irrelevant with regard to the total amount.

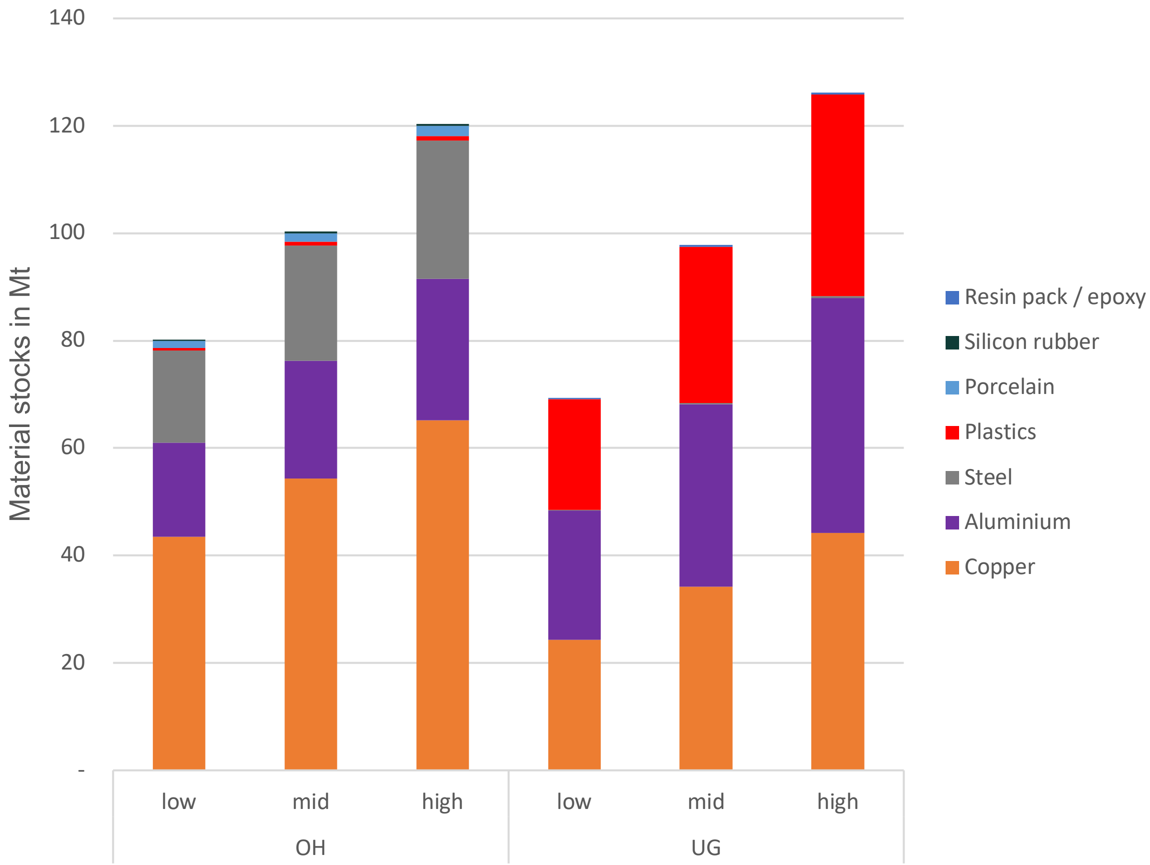
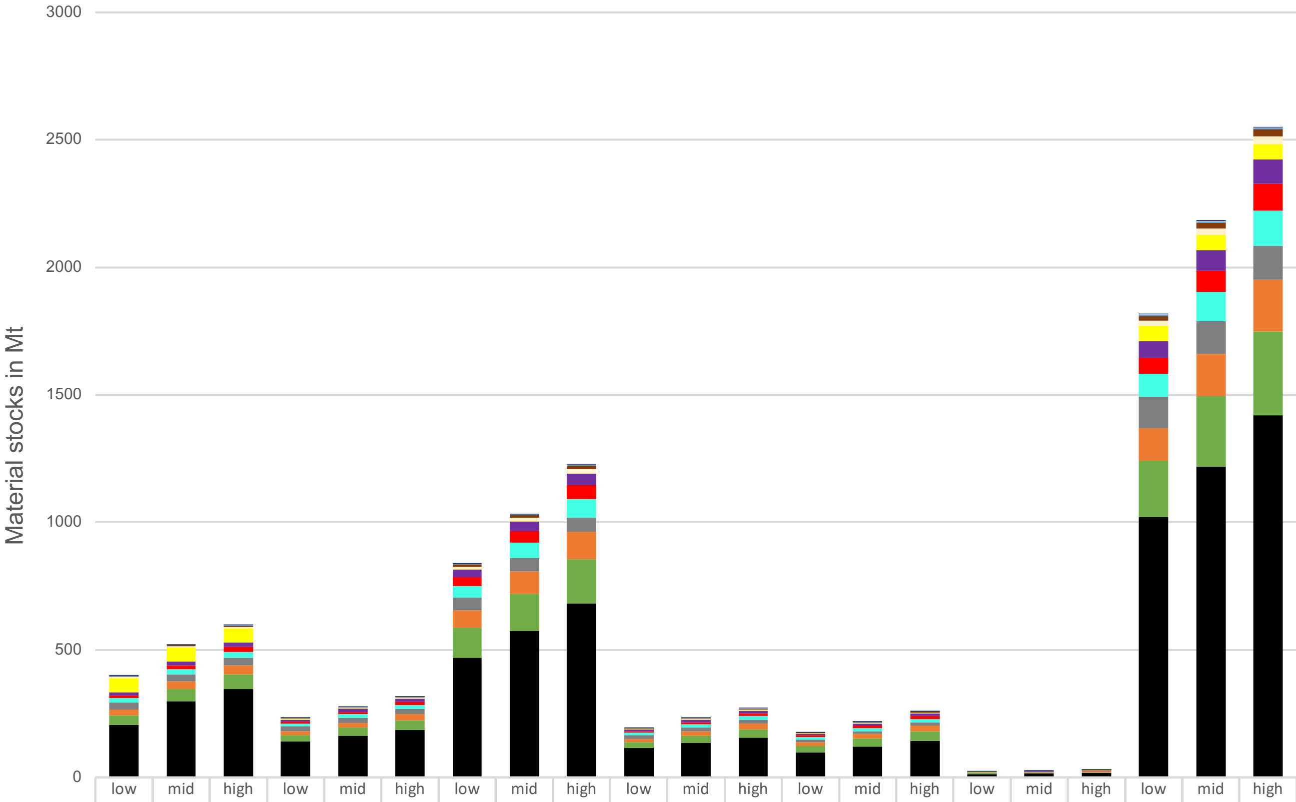


Figure 15: Material stocks in global medium voltage overhead (OH) lines and underground (UG) cables without foundation and towers based on the year 2019 (in Mt).

4.4. Total material stocks of the global electricity infrastructure

This section features the results of the total material stocks in the electricity infrastructure which is the sum of the transmission and the distribution infrastructure (see also previous sections 4.1 for the transmission, and 4.3 for the distribution infrastructure). The data is based on the year 2019 (unless otherwise specified). Fig. 16 exhibits the overall material stocks of the global electricity infrastructure. In sum, material stocks reach a level between 1818 Mt and 2550 Mt with a medium value of 2184 Mt. Concrete makes up around 57% on average, with the concrete foundations in Asia as a major contributor; however, the European and North American transmission infrastructure adds noteworthy quantities of concrete to the total stock.



	Europe			North America			Asia			Latin America			Africa			Oceania			World		
	low	mid	high	low	mid	high	low	mid	high	low	mid	high	low	mid	high	low	mid	high	low	mid	high
Asphalt	2.6	2.6	2.6	0.1	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.1	2.9	2.9	2.9
Zinc	0.3	0.3	0.3	0.2	0.2	0.2	0.6	0.6	0.6	0.2	0.2	0.2	0.1	0.1	0.1	0.0	0.0	0.0	1.5	1.5	1.5
Porcelain	0.9	1.0	1.1	0.6	0.7	0.7	2.0	2.3	2.6	0.5	0.6	0.6	0.4	0.5	0.6	0.1	0.1	0.1	4.3	4.9	5.5
Mineral oil	3.4	4.2	5.0	2.2	2.7	3.3	9.3	11.8	14.2	1.9	2.4	2.8	1.9	2.4	2.9	0.2	0.2	0.3	18.3	23.0	27.7
Paper	3.4	4.3	5.3	2.2	2.8	3.4	9.9	12.7	15.5	1.9	2.5	3.0	2.0	2.6	3.1	0.2	0.2	0.3	19.1	24.4	29.7
Sand	55.7	55.7	55.7	1.3	1.3	1.3	0.8	0.8	0.8	1.6	1.6	1.6	0.3	0.3	0.3	1.2	1.2	1.2	60.9	60.9	60.9
Aluminum	13.0	15.5	18.0	8.8	10.4	12.1	30.9	38.5	46.1	7.1	8.6	10.1	6.8	8.5	10.1	0.9	1.1	1.2	65.0	79.2	93.5
Plastics	11.2	14.8	18.4	7.3	9.6	12.0	33.7	44.5	55.4	6.5	8.7	10.8	7.0	9.3	11.6	0.7	0.9	1.1	63.8	84.4	104.9
Lead	15.8	20.1	24.4	10.1	13.0	15.8	46.4	59.4	72.3	9.0	11.6	14.1	9.4	12.0	14.7	0.9	1.1	1.3	89.0	113.7	138.5
Steel	27.5	28.3	29.1	19.6	20.1	20.6	50.9	53.3	55.6	15.4	15.9	16.3	10.7	11.2	11.7	1.8	1.9	1.9	124.9	129.3	133.7
Copper	22.7	29.3	35.9	14.6	18.9	23.2	67.4	87.3	107.2	13.1	17.0	20.9	14.3	18.5	22.8	1.4	1.8	2.2	127.7	165.2	202.7
Timber	38.5	48.1	57.6	25.2	31.4	37.7	116.4	145.3	174.2	22.6	28.3	33.9	24.5	30.6	36.7	2.3	2.9	3.5	220.0	274.6	329.3
Concrete	205.9	298.2	346.1	141.2	164.0	186.8	470.3	575.8	681.4	114.6	135.2	155.7	99.2	121.5	143.7	13.2	15.3	17.4	1021.0	1220.3	1419.7

Figure 16: Material stocks of the global transmission and distribution system based on the year 2019 (in Mt).

Asia accounts again to the bulk of material stocks with 1025 ± 192 Mt, Europe to 518 ± 76 Mt, North America to 275 ± 42 Mt, Latin America to 231 ± 37 Mt, Africa to 210 ± 39 Mt, and Oceania to 25 ± 3.4 Mt. The entire copper stocks add up to 165 ± 37 Mt and aluminum to 79 ± 14 Mt. Interestingly, the quantity of lead is remarkable with 114 ± 25 Mt. The total steel stock, which is incorporated in a multitude of components, accounts to 129 ± 4 Mt. Fig. 17 shows the global material stocks in the transmission and distribution infrastructure without foundation, ducts, and towers.

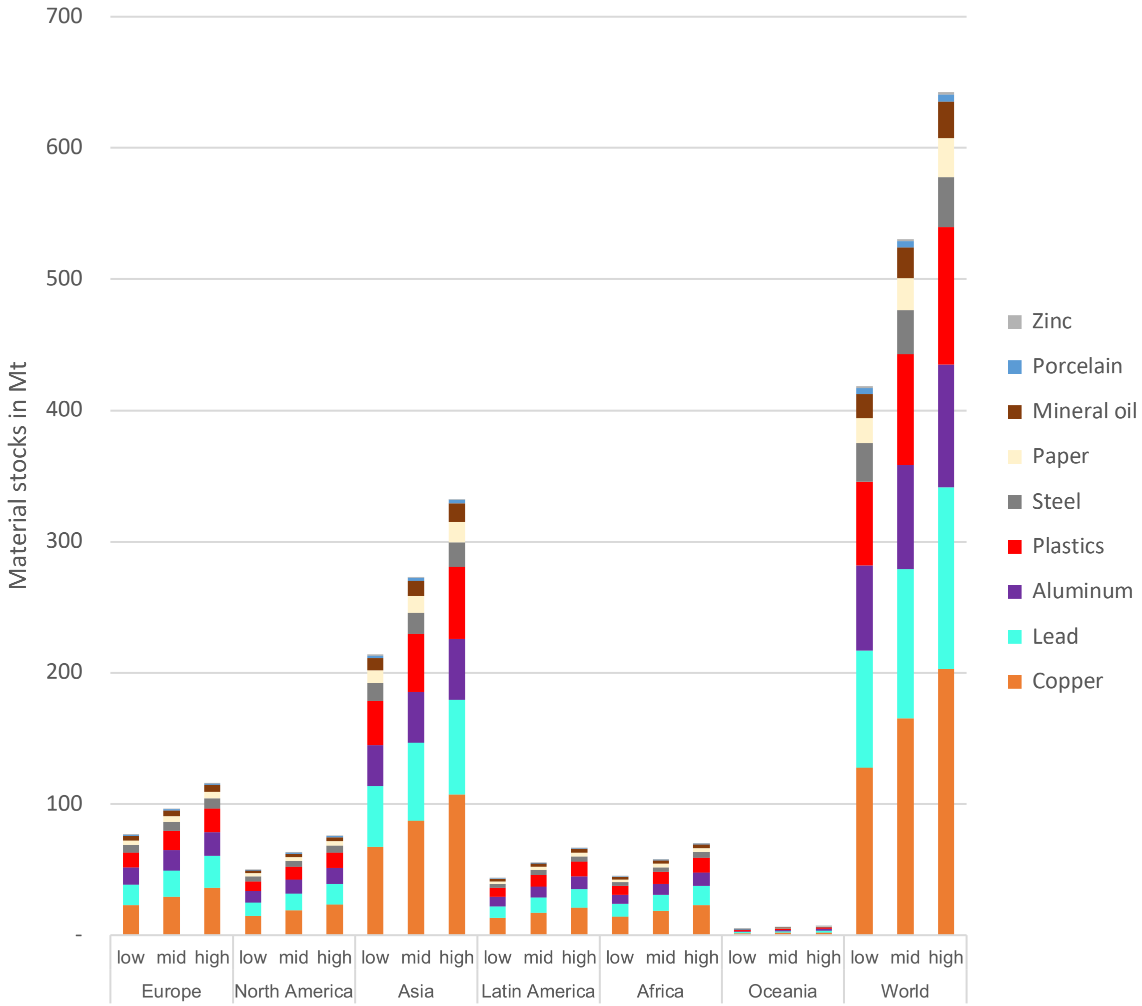


Figure 17: Material stocks of the global transmission and distribution system without foundation and masts based on the year 2019 (in Mt).

Fig. 18 presents material stocks of low-, medium-, and high voltage systems by continent. As can be observed, the proportions of different voltage levels differ to some extent. The global material stock is dominated by low voltage distribution systems in Asia that amounts to 457 ± 104 Mt. The lower share of materials for the transmission system on the global scale compared to Europe can be ascribed to the less developed transmission infrastructure in Asia, Latin America, and Africa. This highlights the greater material intensity of the electricity infrastructure in Europe and North America. Nevertheless, the low voltage distribution system is the most significant with 872 ± 198 Mt, whereas both the high voltage transmission system and the medium voltage distribution system are almost equal with 663 Mt and 649 ± 168 Mt respectively.

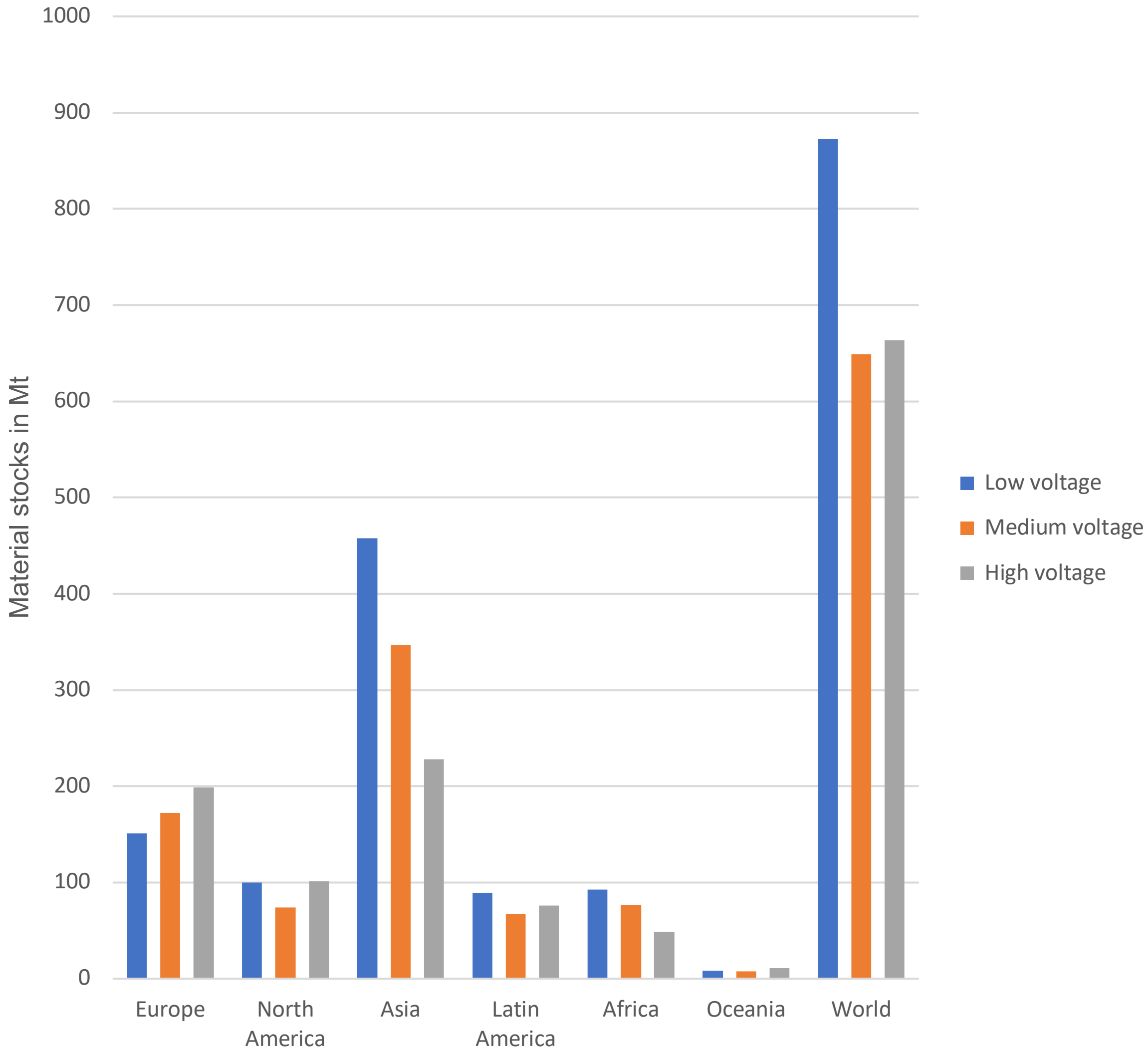


Figure 18: Material stocks in low-, medium-, and high voltage systems by continents based on the year 2019.

The electrification rate in SSA still remains at low levels and merely reached around 45% by 2018. This means that over 600 million citizens lack sufficient possibilities to benefit from energy services. Although substantial progress has been made, around 80% of the citizens who gained access to energy were concentrated in Asian states. Up to now, still almost 70% of citizens worldwide that lack sufficient access to electricity are situated in SSA countries. Of those 70%, nearly 50% are residents of Uganda, Ethiopia, Tanzania, Dem. Rep. Congo, and Nigeria (IEA, 2019a)

Access to electricity is an essential factor that drives material demand for the electricity infrastructure. Fig. 19 gives a graphical overview of per capita material stocks in the electricity infrastructure worldwide. The darker colored countries represent countries with higher material stocks per capita in contrast to lighter colored countries. It can be seen that industrialized countries have a much higher material intensity than SSA countries.

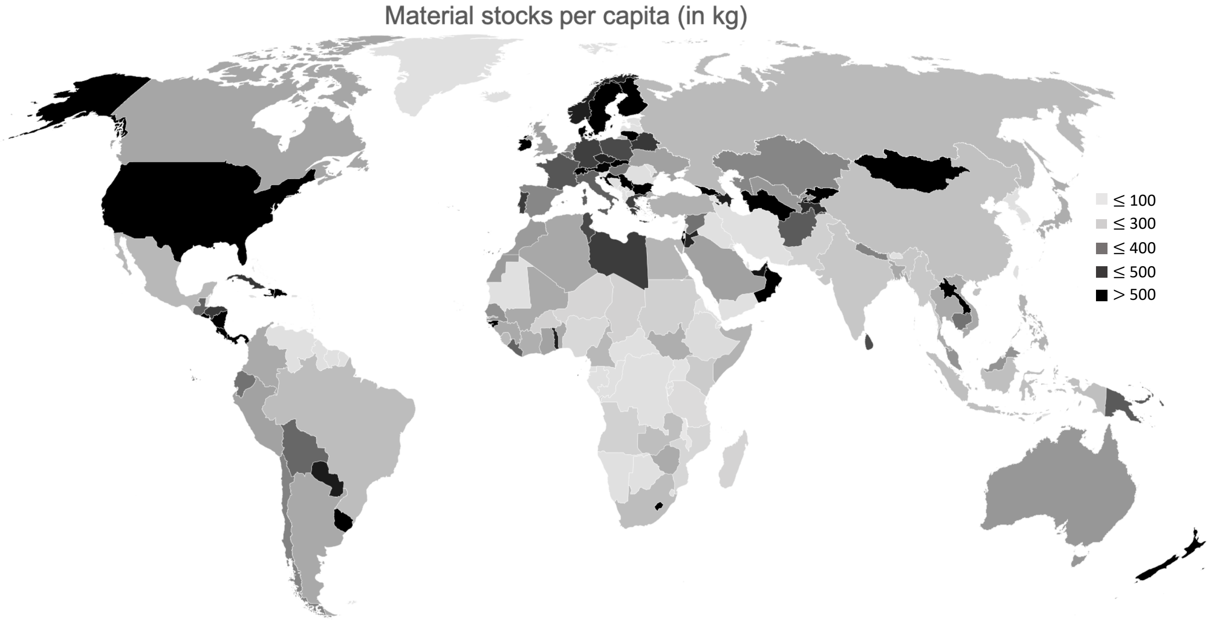


Figure 19: Material stocks of transmission and distribution systems per capita by region based on the year 2019 (in kg/capita).

Additionally, the population density influences material stocks per capita. Countries with a low population density are generally characterized by larger material stocks per capita. This can be attributed to the longer distances that have to be covered in countries with a large area, especially to the presence of more high voltage transmission lines that incorporate considerably more materials per length.

This emphasizes the assumption that population density has diverging effects between the total line length and material stocks. Although the line length rises according to the population density, the countries with lower population density incorporate a higher material stock. This can be attributed to the fact that countries with a low population density are commonly characterized by a higher portion of the transmission system. Since the transmission lines and their respective towers and foundations are much more material intensive, this implies a higher total material stock.

The numerical comparison is provided in Table 13. Citizens in industrialized countries – predominantly located in Europe and North America – have a substantially higher material stock per capita. The global average is 288 ± 48 kg/capita. Material stocks per capita can, however, range from 69 kg/capita in Congo, Dem. Rep., or Malawi, to 1541 kg/capita in Finland. Hence, about 22 citizens of the Dem. Rep. Congo have a material stock equal to 1 citizen in Finland. This unequal distribution is primarily ascribed to the lack of electricity access in developing countries, that is sometimes less than 5% in rural areas of several SSA countries (IEA, 2019a)

Table 13: Selected countries and their respective per capita material stocks (in kg) in the electricity infrastructure based on the year 2019. Countries marked in bold letters are Eurelectric member states with data based on Eurelectric (2011).

Congo	69	**Norway**	537
Malawi	69	United Arab Emirates	562
Uganda	89	**Austria**	591
Romania	106	United States	652
Tanzania	117	**Denmark**	658
Ethiopia	129	Oman	687
Nigeria	130	New Zealand	690
Mozambique	142	Switzerland	695
Niger	145	**Ireland**	767
Madagascar	153	**Slovak Republic**	802
Chad	161	Panama	852
Angola	164	Israel	864
Burkina Faso	167	**Lithuania**	986
Pakistan	169	**Sweden**	1153
Sudan	170	**Finland**	1541

The in-use stock per capita differentiated by material is presented in Table 14. The values vary depending on how much they are used in high-, medium-, and low voltage levels and their respective variance. Approximately 288 ± 48 kg per capita of total material stocks are incorporated in the global electricity infrastructure. About 145 ± 47 kg per capita of concrete is in-use and therefore the major driver of total stocks. Nevertheless, the metals steel, copper, and lead are likewise important contributors, underlining the high metal stocks employed in the electricity infrastructure.

Table 14: Material stocks per capita by material based on the year 2019 (in kg).

	Material stocks per capita (in kg)
Concrete	145.5 ± 47
Timber	34.8 ± 7
Copper	21.2 ± 5
Lead	14.9 ± 4
Steel	13.41 ± 5
Plastics	10.7 ± 3
Aluminum	9.9 ± 3
Paper	3.7 ± 1.3
Mineral Oil	2.9 ± 0.7
Porcelain/Resins	0.9 ± 0.3
Zinc	0.6 ± 0.3
Total	**288 ± 48**

Table 15 provides the per capita in-use stocks differentiated between region and material. The highest per capita stocks can be found in North America, followed by Europe and Oceania. Compared to Africa, material stocks in North America are higher by a factor of 3.3, and in Europe by a factor of 2.3.

Table 15: Material stocks per capita by region and material based on the year 2019 (in kg).

	Europe	North America	Asia	Latin America	Africa	Oceania
Concrete	246.7 ± 79.7	347.0 ± 112.1	130.9 ± 42.3	171.5 ± 55.4	105.4 ± 43.1	236.1 ± 76.3
Timber	59.0 ± 11.7	83.0 ± 16.5	31.3 ± 6.2	41.0 ± 8.2	25.2 ± 5.0	56.5 ± 11.2
Copper	36.0 ± 8.8	50.6 ± 12.4	19.1 ± 4.7	25.0 ± 6.1	15.4 ± 3.8	34.4 ± 8.4
Lead	25.2 ± 6.5	35.5 ± 9.2	13.4 ± 3.5	17.5 ± 4.6	10.8 ± 2.8	24.1 ± 6.3
Steel	22.7 ± 8.9	32.0 ± 12.5	12.1 ± 4.7	15.8 ± 6.2	9.7 ± 3.8	21.8 ± 8.5
Plastics	18.2 ± 4.6	25.6 ± 6.4	9.7 ± 2.4	12.7 ± 3.2	7.8 ± 2.0	17.4 ± 4.4
Aluminum	16.7 ± 5.1	23.5 ± 7.2	8.9 ± 2.7	11.6 ± 3.6	7.1 ± 2.2	16.0 ± 4.9
Paper	5.5 ± 1.5	7.7 ± 2.1	2.9 ± 0.8	3.8 ± 1.0	2.3 ± 0.6	5.2 ± 1.4
Mineral Oil	5.0 ± 1.2	7.0 ± 1.6	2.6 ± 0.6	3.4 ± 0.8	2.1 ± 0.5	4.7 ± 1.1
Porcelain/Resins	1.0 ± 0.3	1.4 ± 0.4	0.5 ± 0.2	0.7 ± 0.2	0.4 ± 0.1	0.9 ± 0.3
Zinc	0.1 ± 0.1	0.2 ± 0.1	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0
Total	**436.0 ± 128.4**	**613.4 ± 180.6**	**231.3 ± 68.1**	**303.1 ± 89.2**	**186.3 ± 54.9**	**417.3 ± 122.8**

Fig. 20 shows the material stocks per land area in kg per km^2. Apparently, there is a strong relationship between material stocks per land area and population density, which is clear because the line lengths (and therefore material stocks) are predominantly driven by the number of the population. The numerical comparison is shown in Table 16. The difference between, for example, Australia, Canada, and Mongolia is very high if compared to Netherlands, Korea, and Bangladesh. Bangladesh has therefore around 340 times more material stocks per km^2 than Australia.

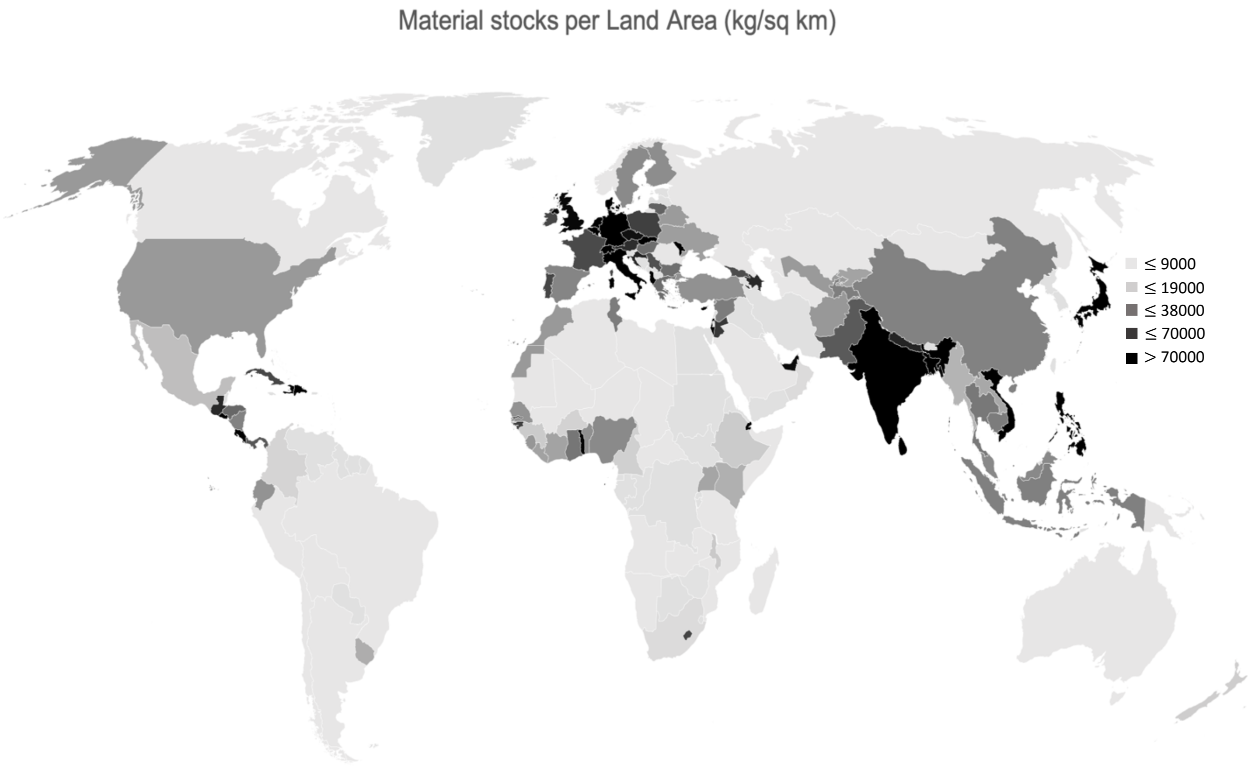


Figure 20: Material stocks (in kg) per land area based on the year 2019 (km²).

Table 16: Selected countries and their respective material stocks (in kg) per km² based on the year 2019. Countries marked in bold letters are Eurelectric member states with data based on Eurelectric (2011).

Australia	971	**United Kingdom**	**76913**
Canada	1102	Costa Rica	80588
Mongolia	1787	Vietnam	81073
Libya	1822	**Italy**	**83517**
Russian Federation	2022	Japan	88864
Kazakhstan	2259	**Slovak Republic**	**90882**
Congo, Dem. Rep.	2571	**Denmark**	**90951**
Mauritania	2573	India	92976
Niger	2578	**Germany**	**112783**
Namibia	3016	**Belgium**	**141794**
Central African Republic	3920	Switzerland	149869
Angola	4066	**Netherlands**	**166677**
Mali	4090	Korea, Rep.	184028
Bolivia	4130	Bangladesh	332328
Argentina	4289	Israel	354982

Fig. 21 demonstrates the material stocks in kg in relationship to electricity consumption in kWh. The largest material stocks per electricity consumption can be primarily found in developing countries in the SSA region and can reach up to 1.75 kg/kWh (Ethiopia).

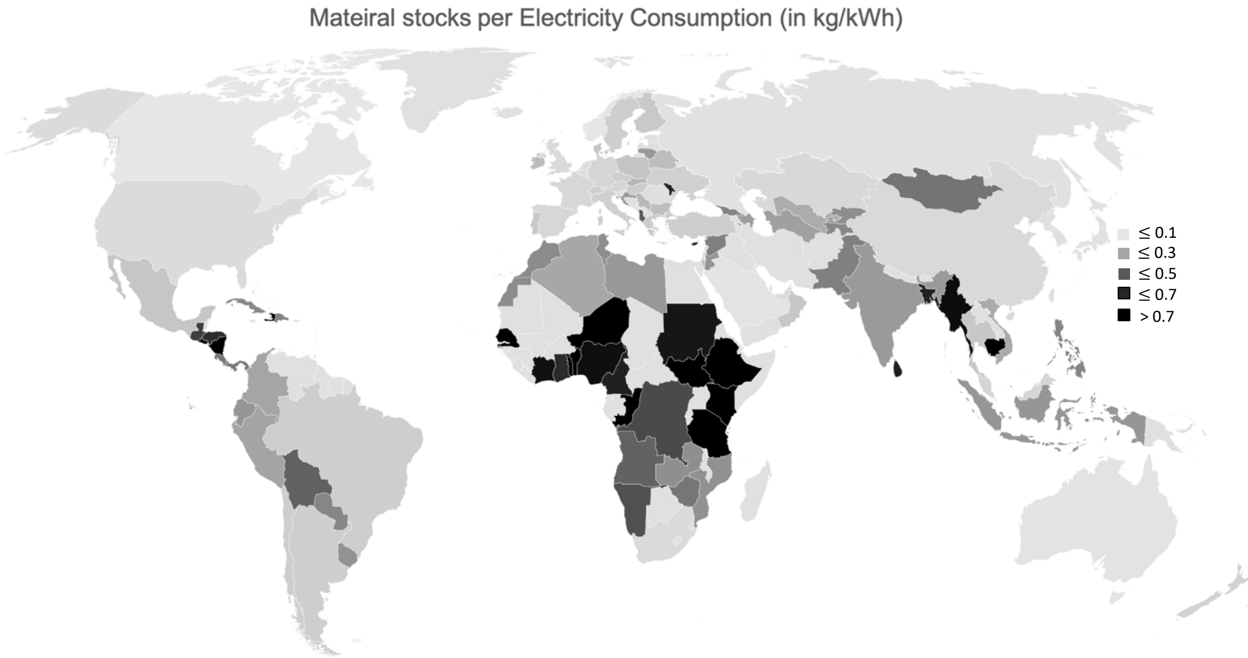


Figure 21: Material stocks (in kg) per electricity consumption based on the year 2019 (in kWh).

Table 17 provides the numerical comparison of material stocks per electricity consumption. Developing countries show an unexpectedly high material intensity, whereas industrialized countries are characterized by much a lower material demand.

Table 17: Material stocks (in kg) per electricity consumption (in kWh) of selected countries based on the year 2019. Countries marked in bold letters are Eurelectric member states with data based on Eurelectric (2011).

Canada	0.02	Zimbabwe	0.43
Norway	**0.02**	Mongolia	0.44
Saudi Arabia	0.03	Angola	0.53
Australia	0.03	Namibia	0.61
Japan	0.03	Congo, Dem. Rep.	0.64
Korea, Rep.	0.03	Guatemala	0.70
Russian Federation	0.03	Honduras	0.79
Romania	**0.04**	Ghana	0.79
Netherlands	**0.05**	Bangladesh	0.84
Belgium	**0.05**	Cameroon	0.85
United States	0.05	Sudan	0.89
United Arab Emirates	0.05	Nigeria	0.93
South Africa	0.05	Tanzania	1.13
United Kingdom	**0.05**	Kenya	1.16
China	0.05	Senegal	1.36
Kazakhstan	0.06	Ethiopia	1.75

One would first assume that material stocks per electricity consumption are lower in developing countries, where the high voltage transmission infrastructure is less developed. Less transmission infrastructure would therefore mean that a smaller amount of materials is used because the transmission infrastructure is highly material intensive. However, this appears to be different here.

Possible explanations are that in developing countries, households get electricity only for a few hours per day and the electricity consumption per household is generally much lower than in industrialized countries. The grids must be dimensioned on the basis of the peak performance, so the material stocks must be relatively equal to grids in industrialized countries, regardless of whether electricity is only used for one hour per day or for 24 hours. Another reason could be the electricity consumption for heating, which is much lower in countries listed on the right-hand side in Table 17 with higher average outside temperatures. Another aspect could be that household connections in developing countries are designed for much lower outputs, and thus have much smaller line and cable diameters than in industrialized countries. Furthermore, the regression model is based on data of Eurelectric member states (for detailed list see Appendix A), USA, India, and Indonesia. The lack of data from African countries which are not incorporated in the regression model may result in too optimistic values for the line lengths. Therefore, if the estimated line lengths are overestimated but the electricity consumption is low, this would cause a higher material stock per electricity consumption. Since this work only differentiates the material intensities according to voltage levels and does not take regional differences into account, it could be that the stocks in distribution systems in developing countries are overestimated.

4.5. Outlook

The material stock in the electricity infrastructure largely depends on the population development and the population that has access to electricity. The following scenario of material stocks incorporated in the infrastructure is based on the population development projected by the United Nations (2019) and assumptions about electricity access made by IEA (2019a). The data is based on the year 2019

Fig. 22 illustrates how the amount material stocks expanded since the beginning of the 21st century, and how this stock might grow until the end of this century. In this scenario, it is assumed, that according to SDG 7 “Access to Affordable and Clean Energy”, the global population will receive universal access to electricity by 2030. No effects of RES deployment and no substitution between different materials are considered. This means that also citizens in the least developed countries will benefit from access to affordable, reliable, sustainable, and modern energy for all, hence the access to electricity will be 100%. Clearly, this requires a sharp expansion of the electricity infrastructure, particularly in developing countries.

According to this scenario, the in-use quantities almost double during the entire century to over 3.1 Gt in the year 2100 of total material mass compared to 1.6 Gt in the year 2000 (see also Appendix G). The graph shows a strong expansion of material stocks in the electricity infrastructure until the year 2030 with following reduced growth rates. This is owing to efforts of facilitating electricity access predominantly in the SSA region. The increase in SSA countries is driven by two factors: first, the high fertility rates and population growth in this region as predicted by the UN, and second, the fact that a large number of citizens in the SSA, that currently suffer from low electrification rates, will gain advanced electricity access in this scenario. Hence, the total number of people that benefit from electricity services are assumed to rise exponentially. Moreover, high contributions will come from Asia; although many Asian countries are already well-electrified, the large population of Asian countries will nevertheless be the key driver for rising material demand, despite its decelerating population growth rate. European countries will, however, not perceive substantial accumulation of materials, because the electrification rates are already at 100% ever since the 1960s, and the population growth is by far not comparable to Asian and African countries. This also holds for North America, where the infrastructure is well-developed, and the population growth is characterized by stagnation.

Universal electricity access by 2030 will possibly increase the in-use copper stocks by 30 Mt and until 2050 by over 50 Mt compared to now. In addition, the infrastructure could require 15 Mt more aluminum in 2030 and almost 25 Mt in 2050. Further demand for lead of 20 Mt may occur by 2030 and 40 Mt by 2050. Overall, the entire material stock might exceed 2500 Mt in 2030 compared to current 2180 Mt, corresponding to an increase in material consumption 34 Mt annually (from 2019). Copper stocks could rise to roughly 260 Mt by 2100 and steel to 165 Mt. Aluminum stocks might reach 120 Mt compared to around 80 Mt today. Additionally, the included lead may perhaps amount to nearly 180 Mt. The largest masses will obviously be concrete and timber (1700 Mt and 420 Mt, respectively). The total material in-use stocks could amount to about 2500 Mt by 2030 and 2800 Mt by 2050. In the very long-term, total material stocks may amount to more than 3200 Mt, which would correspond to a 70% increase compared to current levels (see also Appendix G).

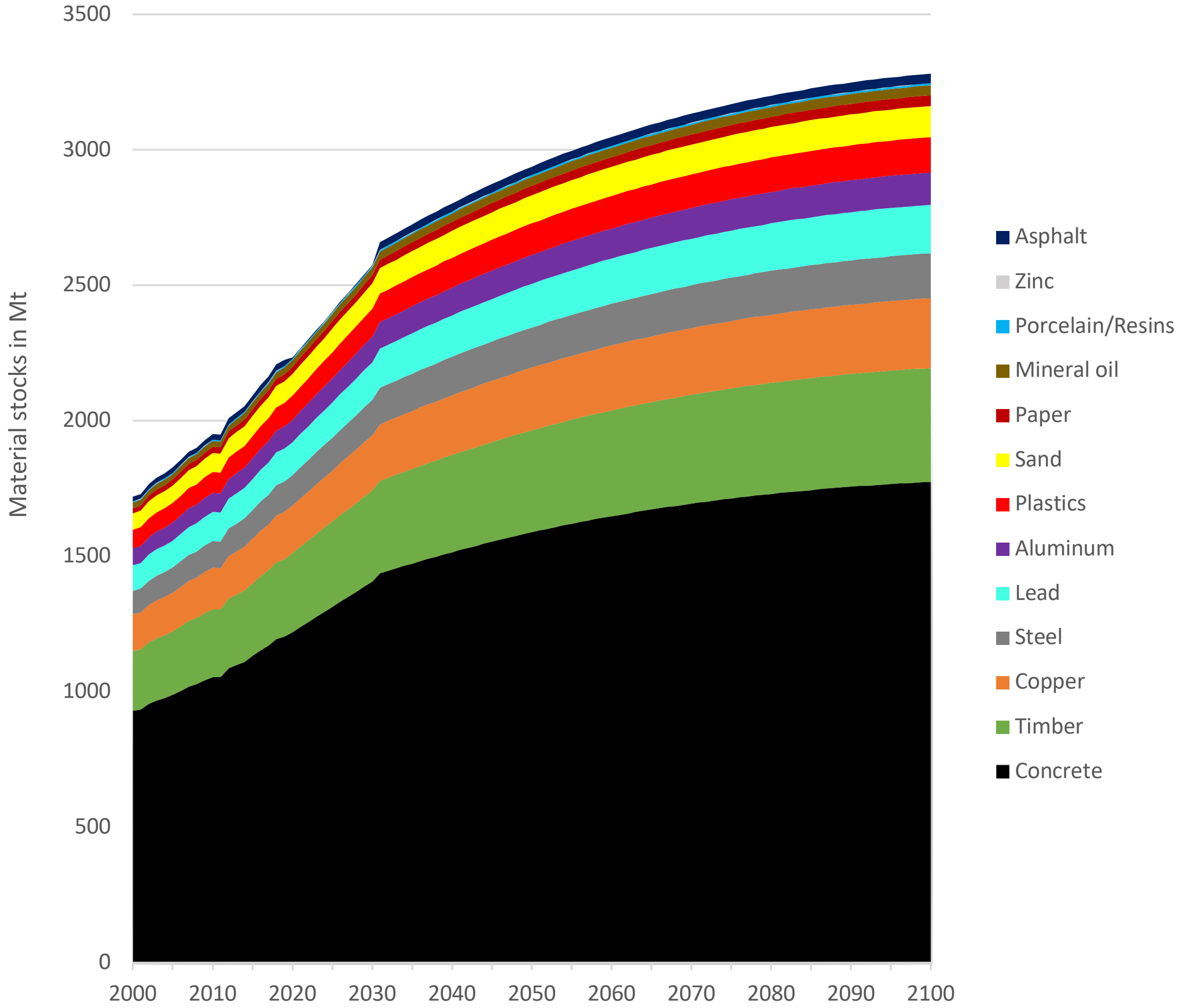


Figure 22: Past and future development of material stocks in the electricity infrastructure. It is assumed, that there is universal electricity access by 2030. Projection is based on data from the United Nations (2019) and from IEA (2019a) about projection of electricity access. Ensuring universal access to affordable, reliable, and modern energy services means that every citizen on earth gains universal access to electricity and clean cooking by 2030 (IIASA, 2018).

5. Discussion

In this section, the results from the previous section (4) are put into relation to total material in-use stocks. Additionally, the stocks are compared to the global reserve and resource base, and to the annual production. Options for more sustainable resource patterns are elucidated in section 0, and the growing resource demand in the context of relevant Sustainable Development Goals is discussed in 0.

5.1. Comparison with total in-use stocks, reserves and resources

As has been demonstrated in the previous section, the electricity infrastructure incorporates substantial amounts of materials. The most viable components by weight are concrete, timber, and steel for the foundation, cable ducts and masts, but also metals including copper, lead, and aluminum. Residual components are plastics, paper, mineral oil, porcelain, resins, and zinc.

The extraction and manufacturing of iron, aluminum, copper, zinc, and lead is highly energy intensive, especially the production of primary metals. In countries with large copper production capacities such as Chile, the copper industry is currently the major energy consumer (Alvarado et al., 2002). It is expected, that the demand for copper will grow in the future and that the ore grade will decline, thus the energy needed for copper fabrication will increase (Kuckshinrichs et al., 2007). In 2012, the production of merely six metals including iron, aluminum, copper, manganese, zinc, and lead accounted to 10% of the primary energy consumption worldwide, and has increased from 2007 to 2012 by 4 EJ/y to 52 EJ (Fizaine and Court, 2015).

Table 18 compiles available information regarding the demand, availability of resources and reserves of materials that are employed in the electricity infrastructure. Resources are commonly perceived as materials that are naturally occurring in the Earth´s crust and are realistically available for eventual economic extraction in the future. Reserves are usually identified as the fraction of resources which is discerned as economically feasible for current extraction. Clearly, the boundaries between resources and reserves are variable and influenced by technical, economic, and legal factors (Winterstetter et al., 2015). Based on this comparison, the significance of materials in the electricity infrastructure is discussed in the following sections.

Table 18: Material stocks in the context of resource availability. Total in-use stocks, in-use stocks in the electricity infrastructure, resources and reserves are given in Mt, and annual production in Mt/yr.

	Resources	Reserves	Annual production	Total in-use stocks according to the literature	In-use stock in the electricity infrastructure (results from this study)	Share electricity infrastructure / total in-use stocks (%)
Sources	Pauliuk et al. (2013), Rauch (2009),	Boryczko et al. (2014), Tilton (2003), Pauliuk et al. (2013), Sverdrup et al. (2015), Liu et al. (2013)	Boryczko et al. (2014), Sverdrup et al. (2015)	Pauliuk et al. (2013), Rauch (2009), Wårell (2014), Liu et al. (2013), Mao and Graedel (2009), Gerst and Graedel (2008),		
Steel	170000	-	1600	14800 – 16000	129 ± 4	0.8 – 0.9
Aluminium	46000	16000 - 25000	120	630	80 ± 14	10 – 15
Copper	5820 – 7730	1778	12	340 – 400	165 ± 37	32 – 59
Lead	226 – 415	64	5	25	114 ± 25	356 – 556
Zinc	610 – 630	190	8	205	1.5	0.7
Timber	-	-	-	12646	275 ± 55	1.7 – 2.6
Paper	-	-	-	1200	25 ± 5.	1.6 – 2.5
Plastics	-	-	-	2700	85 ± 20	2.4 – 3.9
Concrete	-	-	-	315800	1220 ± 199	0.3 – 0.4

5.1.1. Metals

Copper

Copper is an essential part of numerous electrical appliances as well as of heat and cooling equipment and has witnessed large growth rates during the last decades (Spatari et al., 2005). The high diversity of various applications and its moderate price has made copper an indispensable metal in modern society that ranks third, following iron and aluminum with respect to the amount (Glöser et al., 2013). The variety of applications and low price of extraction explains the worldwide rise in copper demand in recent times (Bader et al., 2011). Due to its high electrical and thermal conductivity and corrosion resistance, it is widely employed in several sectors, including the sectors Building and Construction, Consumer Electronics and the Electricity Infrastructure. The latter is often recognized as one of the largest copper stocks in many industrialized cities (Krook et al., 2011).

According to Gerst (2009) the electricity infrastructure accounts to 32% of copper stocks worldwide after the building and construction sector, and Elshkaki et al. (2016) find that the infrastructure is even the largest sector with around 25%. As stated by Daigo et al. (2009) and van Beers and Graedel (2007), it corresponds to 22%. It is understandable that the share of copper stocks in the electricity infrastructure evaluated in different studies is hard to compare with each other, since the extent of the term “infrastructure” used in publications covers diverging components, comprising power cables, telecommunication cables, power generators, and train overhead lines. Moreover, it is challenging to relate previous outcomes to results from this work. Because components like telecommunication cables, power generators and train overhead lines are not covered here, a proper appraisal of estimated copper stocks in relation to other results is impeded. Nonetheless, a general trend can be observed.

Several studies evaluated the in-use copper stocks by region and sector, however, the results are not always uniform. Daigo et al. (2009) has, among other sectors, estimated the copper stocks in electrical conductors of power and telecommunication cables in Japan. They found that the copper stock in this sector account for about 25% of the total in-use stock in 2005, corresponding to around 5 Mt. Spatari et al. (2005) assessed the copper stocks in the electricity infrastructure in North America and discovered in-use stocks of almost 28 Mt by the end of the 20th century. On a global scale, Ecofys (2014) calculated copper stocks in the low-, and medium voltage distribution system of around 163 Mt. Soulier et al. (2018) approximated the copper stocks in the infrastructure to around 15 Mt within the EU, corresponding to almost 20% of the total copper stocks. Table 19 gives an overview of in-use copper stocks of several country evaluations in comparison to this work.

Table 19: Overview on results of copper stocks in the electricity infrastructure evaluated by several authors and compared to this work (in Mt).

	Country	Previous studies	This work
Daigo et al. (2009)	Japan	5	3 ± 0.7
Soulier et al. (2018)	EU	15	17
Spatari et al. (2005)	North America	28	19 ± 4.3
van Beers and Graedel (2007)	Australia	0.8	0.7 ± 0.2
Ecofys (2014)	World	163	165 ± 37

It can be seen, that estimations throughout this work are in the same order of magnitude as found by other studies. In comparison to copper stocks analyzed in Japan (see Daigo et al., 2009) and North America (see Spatari et al., 2005), the copper stocks in this work are underestimated. Contrarily, this work slightly overestimates the copper stocks in the EU in comparison to Soulier et al. (2018) (no range because results are based on data of Eurelectric member states with official statistical data, see also section 3.3.1 and 4.2). The estimates for the World and Australia in this work match well with the value of Ecofys (2014) and van Beers and Graedel (2007).

The amount of the worldwide anthropogenic copper reservoirs can only be roughly estimated. Gerst (2009) modeled several scenarios of current and future copper in-use stocks. According to their outcomes, global copper stocks amounted to about 400 Mt in 2020. They additionally predict a growth of copper stocks to somewhere between 1450 and 2100 Mt by the year 2100.

This would be equal or more to current known and mineable reserves of 1778 Mt. Elshkaki et al. (2016) state that the demand for copper will exceed the reserves by 2050, thus copper reserves will become depleted more rapidly than expected. According to them, the majority of copper manufacturing countries will be incapable to maintain their present production volumes by 2050, due to the exhausted reserve base. Therefore, society could face severe threats of copper exhaustion by the end of this century with the electricity infrastructure as a prominent part.

Results from this work show a copper in-use stock in the electricity infrastructure of about 165 Mt with a relatively wide range from 129 to 202 Mt. Although global estimates of anthropogenic copper stocks vary, the electricity infrastructure evidently incorporates an important share of the global copper stocks. Particularly until 2030, the copper stock in the electricity infrastructure is expected to grow rapidly, owing to the expansion of the infrastructure in SSA countries mixed with high population growth. Moreover, large interconnection projects in Europe could entail a considerable expansion of high voltage submarine cables. Due to its operational benefits, high shares of RES call for the intensification of efforts to implement an international and intercontinental electricity grid. Several options of integrating clean energy resources exist, such as geothermal energy from Iceland and hydropower Norway in the continental European electricity grid (Hammons et al., 1993, Chatzivasileiadis et al., 2013). This would require major investments in submarine transmission cables. As a result, copper stocks may increase due to the fact that high voltage submarine cables can require 8.6 tons per kilometer (see section 3.3.2).

Around 208 ± 47 Mt of copper could be installed by 2030 and 230 ± 52 Mt by 2050 if universal electricity access is assumed based on the global population growth projected by the United Nations (2019) (see Appendix G). This could amount to over 18% by 2030 and 22% by 2050 with regard to copper reserves. Until 2100, the anthropogenic copper reservoirs in the global electricity infrastructure may correspond to over 26% of total copper reserves, thus, significantly shape the relationship of copper supply and demand. Additionally, increased copper demand triggered by the expansion of the electricity infrastructure will have a noteworthy impact on anthropogenic climate change, caused by the high energy requirements of copper production processes.

Aluminum

Aluminum is the most abundant metal and third most abundant element in the earth´s crust. It is employed in a large variety of appliances due to its valuable properties, including good corrosion resistance, heat and electric conductivity, and its lightweight. In terms of consumption with respect to the mass, it ranks second after steel and it is expected that the demand will grow fast throughout the next decades (Recalde et al., 2008). The increase in the demand of primary aluminum will not slow down until 2060 (Sverdrup et al., 2015).

In 2009, the worldwide in-use stock of aluminum was estimated to be about 630 Mt (see Liu et al., 2013). The most significant sectors comprise Transportation, Equipment, Building, and the Infrastructure. The latter encompasses one major sector: Electric transmission and distribution (Recalde et al., 2008). Wang and Graedel (2010) found that electricity transmission and distribution is a momentous contributor to the total aluminum stock and accounted to about 6.5 Mt in 2005 in China. The EAA (2006) claim that 18% of the total aluminum stock is integrated in the transmission and distribution system, and is a main repository for aluminum.

Due to its high abundance in the earth´s crust, there is no current risk of scarcity, at least in the short-, and medium-term. Altogether, the mineable amounts of aluminum are equal to roughly 16000 Mt. If the recyclable amounts at present and the approximated hidden amounts are added to the known reserves, total extractable resources would reach up to 46000 Mt (Rauch, 2009, Sverdrup et al., 2015). However, environmental implications of aluminum are less its scarcity, but its highly energy intensive production processes. CO_2-eq emissions, basically related to the manufacturing of aluminum, currently represent around 1.1% of global GHG-emissions.

Its much lower mass in the infrastructure compared to copper can be explained by first, its usage predominantly in transmission systems which length is considerably shorter, and second, its lighter weight, thus having less impact on total mass. Aluminum in-use stocks in the electricity infrastructure could reach 100 Mt and by 2100 even 120 Mt, by 2030. As elucidated above, this will not have significant impacts on extractable reserves, but stands in sharp contrast to climate change mitigation efforts. If it is supposed that the aluminum sector will have to contribute to the Paris Agreement to limit anthropogenic climate change to 2°C compared to pre-industrial levels, a decline of 50% of GHG-emissions is required. In relation to the expected threefold increasing demand, this would result in 85% reduction in emission intensity, which is extremely difficult to achieve (Liu et al., 2013).

This work estimates current global aluminum stocks in the electricity infrastructure to 80 ± 14 Mt. This corresponds to an eight of total aluminum in-use stocks that is employed in high voltage transmission and medium voltage distribution conductors. The growing share of RES in grids will likely entail a strong expansion of high voltage lines, hence, the in-use stock of aluminum in the transmission infrastructure. Furthermore, the demand of aluminum could increase if substitution of copper in the low-, and medium voltage lines continues. The future aluminum in-use stock in the electricity infrastructure could therefore be underestimated.

Steel

Steel ranks first with respect to the consumption and in-use stocks of all metals in the anthroposphere. It is widely applied in the construction sector, but also for transportation, machinery, containers and other appliances (Pauliuk et al., 2013). Although an inverse U-shaped intensity-of-use curve has been recently observed (meaning that steel-use declines with increasing GDP per capita), global demand is still growing. This is mainly driven by large steel requirements of China, currently accounting for almost 44% of the world steel demand. The global steel consumption is thus still bound to grow and reached 1600 Mt annually by 2010, compared to 600 Mt in 1970 (Wårell, 2014).

The overall in-use stock of steel is much greater than that of aluminum or copper and lies somewhere between 14800 Mt (Rauch, 2009) and 16000 Mt (Gerst and Graedel, 2008), and it is therefore by far the largest among all metals. Global iron resources are high with rough estimations ranging up to 170 Gt (Rauch, 2009).

Similarly to aluminum, the iron resources for steel production are not considered as scarce and may also be sufficient for a long time. However, environmental consequences do not arise from its scarcity or iron mining, but from its highly energy intensive production processes (Pauliuk et al., 2013). In 2009, the steel sector was responsible for 9% of process-related CO_2-emissions (Allwood et al., 2010). This highlights the importance of useful estimates of global steel in-use stocks to better understand global consumption dynamics and its associated climate change mitigating potential (Pauliuk et al., 2013).

According to estimates from this work, the steel in-use stock in the global electricity infrastructure amounts to 129 ± 4 Mt, which is equivalent to about 0.9% of total steel in-use stocks. The stock is foremost driven by the employment of steel lattice towers, but also from ASRC for the high voltage transmission lines, the steel-reinforced concrete foundations and cable ducts. The transmission system is thus characterized by a much higher steel intensity, since steel lattice towers and their steel-reinforced concrete foundations as well ASRC are commonly employed in high voltage systems. Although the steel in-use stock in the electricity infrastructure is rather low compared to other sectors, this portion may increase in the background of the substantial expansion of the high voltage infrastructure.

Lead

A drastically increasing use of lead was observed in the middle of the 20th century followed by a considerable decline. Although current lead use has been substituted by several other metals, there is nonetheless a remarkable in-use stock standing. Applications of lead are generally found in batteries, lead sheet, and lead pipe (Mao and Graedel, 2009).

Global lead reserves account to around 64 Mt (Tilton, 2003), and the global resource stock was identified to reach from 226 Mt (Mudd et al., 2017) to 415 Mt (Mao and Graedel, 2009). The annual production of lead amounts to 5.3 Mt, with China alone being responsible for over 50% (Mudd et al., 2017).

The estimate of the lead in-use stock in the electricity infrastructure in this work is 114 ± 25 Mt. This is a surprisingly high value in relation to the global resource stock (48%) as well as existing reserves (it exceeds the reserves by a factor of almost 1.8 ± 0.5). Lead is employed in the sheath that covers the conductor insulation and protects the cable from current other fault sources and provides a return current for fault current. Herein this work, the lead intensity was assumed to be 2111 kg per kilometer employed in OH lines and UG cables in the low voltage level system. Since the total low voltage level system was estimated to be about 53.8 million km, this results in this relatively high value of lead in-use stocks. Mao and Graedel (2009) estimated the total lead in-use stock to 25 Mt and the global per capita stock to 5.6 kg. This stand in sharp contrast to the results reported here, since this work estimates the global per capita stock to be 14.9 ± 4 kg. There is a rough inconsistency to previous outcomes, but after no other data was found in the literature that indicate lower lead intensities, results in this work and literature data on in-use stocks are inconsistent.

Even though lead is one of the best recycled metals, the reserve base is rather low. Findings from this research indicate that the lead stock in electricity infrastructure sector apparently has hitherto gained only little notice and may thus incorporate unexpected large amounts. Known reserves could be depleted during the 20-30 years, hence, recycling efforts must be increased while reducing the material input in order not to run out of lead (Boryczko et al., 2014).

Zinc

Zinc is commonly applied as a coating agent for numerous alloys to protect from corrosion, but also as a trace nutrient for the fertilizer industry and in the rubber manufacturing (Mudd et al., 2017). The Zinc reserve base is around 190 Mt (Boryczko et al., 2014, Tilton, 2003), and the resources are between 610 Mt (Mudd et al., 2017) and 630 Mt (Rauch, 2009). The annual production volume is at 7.8 Mt (Boryczko et al., 2014, Tilton, 2003). The total in-use stock of Zinc is relatively high compared to its reserves and resources and amounts to 205 Mt (Rauch, 2009).

In the electricity infrastructure, Zinc is employed in steel lattice towers in the high voltage transmission system to prevent corrosion. This work estimated the total Zinc in-use stock in the electricity infrastructure to 1.5 Mt. If compared to the reserve and resource stock, the electricity infrastructure plays a minor role that accounts to less than 1% of total in-use stocks. However, the large-scale expansion of the transmission infrastructure is yet to come due to the introduction of renewables in remote areas which also entails the construction of more steel lattice towers, hence, increases Zinc consumption.

Synopsis

The most significant portion of the infrastructure with respect to available amounts is found in copper. Owing to its moderate reserve base and its simultaneously high usage in conductors, copper makes up a substantial amount not only in relation to the total in-use stock (32-59%, see Table 18), but also to global reserves. Despite the total aluminum reserves and resources are high, the electricity infrastructure represents an essential fraction of the total in-use stock (10-15%, see Table 18). Although aluminum stocks may be sufficient for a long time, environmental implications arise from its high energy requirements in the manufacturing process and its growing energy intensity due to decreasing ore grades. The incorporated steel in the steel lattice towers, steel-reinforced concrete foundations and cable ducts, as well as in aluminum steel-reinforced conductors, amounts to a relatively high quantity; however, in relation to its total in-use stock and annual production, it remains of minor importance. Nevertheless, the same thing that applies to aluminum also applies to steel, namely its high influence on global climate change. Zinc, as a coating agent to prevent corrosion of the steel lattice towers, is less significant, both with respect to the total in-use stock and to the total available reserves and resources. The high amounts of lead that are incorporated in the sheath of the conductors represent an unanticipated large magnitude. Estimates from this work vastly exceed the results from previous work that examined the total in-use stock. The in-use stock of lead in the electricity infrastructure is estimated to be even higher than global reserve base and embodies a major share in relation to the total resource stock, however, results are inconsistent to previous works.

5.1.2. Bulk materials and others

Besides the above-mentioned metals, the electricity infrastructure contains noteworthy amounts of concrete, timber, paper, and plastics. Concrete makes up by far the largest amounts of both, total in-use stock and in-use stock in the electricity infrastructure. The in-use stock in the electricity infrastructure of those materials are, however, relatively low compared to the total in-use stock. The share of timber, paper, plastics, and concrete is 2.2 %, 2.0%, 3.1%, and 0.4% respectively (for comparison, see Table 18). Stocks in the electricity infrastructure of these materials are therefore, with respect to its utilization in other sectors, of rather minor importance.

However, the manufacturing of concrete requires large amounts of energy and is a noteworthy contributor to global GHG-emissions. The cement sector is currently accountable for about 9% of global GHG-emissions and has witnessed considerable growth rates during the last few decades, primarily attributed to the rising demand for concrete in China (Kajaste and Hurme, 2016). The related CO_2-emissions in the cement production processes arise from mainly calcination and its high energy usage. This can cover up over 50% of process-related CO_2-emissions in several countries such as Canada (Worrell et al., 2001).

As can be gathered from Table 18, the electricity infrastructure contains 1220 ± 190 Mt of concrete, which is mainly used for tower foundations and cable ducts. The amount of employed concrete in foundations rises according to the voltage level, thus, the transmission system incorporates the bulk of concrete stocks. Again, a large-scale expansion of the transmission infrastructure as a result of high RES deployment and improved electricity access will have a substantial impact on further concrete demand. However, the concrete demand could be reduced if UG cables in the low-, and medium voltage system are substituted by OH lines. This is because cable ducts of UG cables in the low-, and medium voltage system require less material per kilometer.

5.2. Options for more sustainable resource patterns

The provision of energy services is a fundamental prerequisite for socio-economic activities. Moreover, electricity as a form of energy has gained remarkable ascendency during the last decades and is now an integral part of many basic human activities. This profound reliance on electricity makes dematerialization efforts in the electricity sector particularly challenging, given that the opportunities of substitution are very limited. In addition, material consumption of the electricity infrastructure sector and the associated environmental burdens largely remained neglected during the vigorous rise of electrical energy. However, facing population and economic growth, RES deployment to meet GHG-reduction targets, and the general growing energy usage, the material demand of the electricity infrastructure becomes increasingly significant. Several routes to reduce electricity infrastructure-related metabolic activities and the accompanied pressures upon the environment are discussed in the following chapter

5.2.1. Recycling

Materials sourced from secondary resources are crucial to close the loop of material flows in the circular economy. In theory, the reusability of metals is unlimited. However, recycling faces major challenges that impedes the increase of recycling rates. First, metals are frequently becoming more and more impure if they are derived from secondary sources. If materials proceed along the processing chain, the separation of products containing a multitude of diverse materials becomes increasingly difficult (Allwood et al., 2011). Additionally, metals in contemporary products are employed in complex alloys or composite materials which drives the costs of collection, separation, and reprocessing (Haas et al., 2015). The lifetime of lines and cables used in the electricity infrastructure differs by country, but most authors indicate a lifetime of around 40 years (see Arvesen et al., 2015, Gargiulo et al., 2017, Jorge and Hertwich, 2013, Jones and McManus, 2010). Timber poles are characterized by a longer lifetime that can range to over 70 years and can be cost-efficiently re-utilized, for example by farmers (Jones and McManus, 2010). The following section gives insights of recycling efforts regarding materials in the electricity infrastructure.

Overhead lines and Underground cables

UG cables are buried below ground and are usually not recovered for recycling (Jones and McManus, 2010, Wallsten et al., 2013). Studies from Sweden found that cable recovery and following recycling cannot be economically justified because the costs of uncovering, extracting, and transporting obsolete cables to recycling factories cannot be covered at current prices of several scrap metals (Krook et al., 2011). However, the cable recovery and recycling rate could be increased if obsolete cable extraction is combined with maintenance work on the grid. Such integrated projects are profitable only if a certain amount of metals (copper, aluminum, or lead) can be recovered and, additionally, materials from the entire system are recycled. Therefore, the recycling of materials should not merely focus on metals employed in conductors, but also insulation, sheath and jacketing material has to be reconditioned and recycled likewise. Today, this insulation, sheath and jacketing material that mainly consists of paper and plastics is commonly burned in waste incineration plants.

Effective strategies for market-diffusion of secondary materials from UG cables include enhanced cable recycling, higher prices for scrap metals, and non-digging technologies of cable employment (Krook et al., 2015). Conversely, materials in OH lines are recovered to a great extent. At least metals in conductors (copper, aluminum, lead) are recycled to 95% (Jones and McManus, 2010), or nearly to 100% (Wallsten et al., 2013); however, paper and plastics as insulation or jacketing material are also incinerated due to their heterogenous composition that aggravates separation and reprocessing.

Copper

Copper is the metal that requires the most attention considering recycling. If the in-use stock in the electricity infrastructure is compared to the total in-use stock and available reserves, the current global average recycling rate of around 43% shows need for improvement (Rauch, 2009). If the global copper in-use stock in the electricity infrastructure increases to 230 Mt by 2050 (see Appendix G), this could impose serious threats of scarcity. Moreover, it is expected, that the total copper demand will continue to grow between 275 and 350 % until 2050. Energy requirements for copper production may therefore rise up to 2.4% of the total energy demand by 2050, in contrast to current 0.3% (Elshkaki et al., 2016). It is obvious, that one of the vital means to reply to scarcity issues is to intensify efforts for improved recycling. Further methods to account for copper scarcity involves urban mining from obsolete (“hibernating”) copper stocks.

The accumulation of metal stocks occur predominantly in urban regions, which can be higher by a factor of more than a hundred in contrast to rural areas (van Beers and Graedel, 2007). Areas with a high population density are considered to incorporate high stocks of metals, thus, future metal mining could be much more cost-efficient if metals are spatially concentrated. Since lines and cables of low-, and medium voltage distribution systems are principally built in urban areas to distribute electricity to households and offices, the material in-use stocks of the electricity infrastructure located in cities therefore represent considerable copper mines. Significant copper stocks are abandoned and remain unused under the ground for several decades, emphasizing the potential of hibernating copper stocks.

Research from Sweden shows that in the City of Linköping, hibernating copper stocks from power cables that have accumulated throughout the past 40 years below ground amount to 123 tons, corresponding to 1 kg per capita (Krook et al., 2011). At current copper prices, such resource reservoirs from hibernating stocks could efficiently be utilized if combined with maintenance work on the grid (Wallsten et al., 2013). According to estimations from Krook et al. (2011), about 185 kg per kilometer on average are hibernating copper stocks in Sweden´s low voltage and medium voltage distribution system. They estimate the total hibernating copper stock in Sweden to about 90000 tons, which is equal to 60% of Sweden’s annual copper consumption. If the same assumptions of their research are applied to this work, this would amount to roughly 2.9 ± 0.6 Mt of obsolete copper in Europe that remain unused underground. This corresponds to approximately one sixth of the total in-use stock with respect to the electricity infrastructure. This shows that urban mining has some potential to mitigate resource scarcity in industrialized countries.

Aluminum

Though the reserve and resource base of aluminum is fairly high, increasing the recycling rate can be fully justified by its considerable energy savings by using secondary sources. Owing to the fact that processes from primary aluminum production are accountable for 90% of GHG-emissions during aluminum manufacturing, recycling from post-consumer scrap is able to cut the lion´s share of emissions (Liu et al., 2013). The current recycling rate of around 58% shows plenty of room for improvement.

Steel

The recycling rate of steel is fairly high; however, GHG-emissions from the steel sector are remarkable, and an important lever for climate change mitigation. In 2006, the manufacturing of steel accounted to 25% of industrial CO_2-emissions (Allwood et al., 2010). Moreover, steel is the most abundant metal in the built environment of the anthroposphere and effective recycling can consequently influence the demand for global raw material extraction. For instance, improved recycling rates from 71% to 91% could lower the requirements for total raw materials by 1.3% globally (Haas et al., 2015).

5.2.2. Off-grid and mini-grid applications

The main obstacle of increased electricity access, especially in SSA, is the absence of a functioning electricity grid. Rural areas of numerous SSA countries such as Chad, Mozambique, Central African Republic, or South Sudan, suffer from electrification rates below 5%. Additionally, the poor combustion efficiency of conventional biomass cooking stoves has often been declared as a root cause of indoor air pollution, which is among the leading causes of mortality and morbidity related outcomes (Lim et al., 2012, Rao et al., 2013).

The barriers for improved electricity access are geographical, financial, political, and social factors such as poverty, the lack of organizational capacity, donor dependency, and the coverage of long-distance transmission (Ahlborg and Hammar, 2014). One possibility to circumvent those problems could be the deployment of off-grid and mini-grid applications that makes large infrastructural capacities for electricity transmission obsolete. Rural clean energy development includes the utilization of PV panels on rooftops that are capable to electrify remote rural areas in the SSA region while reducing their carbon footprint by using RES (Karekezi and Kithyoma, 2002, Chaurey and Kandpal, 2010). Here, I argue that this could also contribute to reducing the material demand of the transmission infrastructure. If RES available on site could supply enough electricity to villages, there is no longer any need to establish large capacities for electricity transmission and distribution. Rural off-grid RES deployment would reduce the transmission system related material demand and decouple material use from increased access to electricity. Since particularly the construction of the transmission system is highly material intensive, efforts to employ off-grid and mini-grid applications through RES in remote rural SSA can entail important synergies. This could represent essential means to leapfrog both, carbon emissions in compliance with the Paris Agreement, and increasing material consumption with the associated construction of a transmission infrastructure.

5.3. Synergies and trade-offs in related Sustainable Development Goals

On 25 September 2015, the member states of the UN agreed on the adoption of 17 Sustainable Development Goals (SDGs) in the background of the 2030 Agenda for Sustainable Development. The implementation of such aspirational objectives for human development put sustainable social and economic development as fundamental principle on the international policy agenda (UN, 2015). The SDGs comprise a broad-ranging set of subjects, including desirable targets such as poverty alleviation, gender equality, peace and justice, and climate action. They thus provide a vital roadmap to attain prosperity without transgressing planetary boundaries (IIASA, 2018).

Even though all goals are equally important, the achievement of one goal may come to the expense of another one. It is clear, that not all goals can be reached to the same extent, so inevitable trade-offs have to be made if the synergistic realization is not possible. Knowledge-based policies can provide an essential underpinning to alleviate adverse side effects of achieving one goal. In the context regarding material requirements for the global electricity infrastructure, three relevant SDGs can be identified: SDG 7 "Affordable and Clean Energy", SDG 12 "Responsible Consumption and Production" and SDG 13 "Climate Action". SDG 7 is seen as a key for prosperity in developing countries and an important factor to boost socio-economic development. On the other hand, SDG 12 is imperative for sustainable development in general and a prerequisite to reduce the environmental footprint of human action. SDG 13 is crucial to avoid disastrous effects on biodiversity and irreversible damages to the earth´s ecosystems. The fulfillment of SDGs simultaneously may, however, stand in contrast to each other, as described in the following sections.

5.3.1. SDG 7: Affordable and Clean Energy

SDG 7 has the objective to ensure universal access to clean energy for all, which is predominantly addressed to countries that lack of infrastructural capacities and adequate electricity provision. Ensuring universal access to affordable, reliable, and modern energy services means basically, that every citizen on earth gains universal access to electricity and clean cooking by 2030 (IIASA, 2018). The targets within SDG 7 are, according to the UN (2017), defined as:

- Ensuring universal access to affordable, reliable, and modern energy services by 2030
- Substantially increasing the share of renewable energy in the global energy mix by 2030
- Doubling the global rate of improvement in energy efficiency by 2030
- Enhancing international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology by 2030
- Expanding infrastructure and upgrade technology to supply modern and sustainable energy services to all developing countries, in particular least developed countries, small island developing States, and land-locked developing countries, in accordance with their respective programs of support

Recent data about energy access show promising results. The International Energy Agency reported that the citizens without access to electricity declined by 140 million in just one year from 1 billion to around 860 million between 2017 and 2018. The majority of this progress accounts to India being responsible for more than 50% of this gain. Almost 70% of people worldwide without electricity access are located in SSA countries. Even though remarkable achievements have been reported in countries such as a Kenya and Rwanda, around 600 million citizens are still suffering from no access to electricity in SSA. In order to realize SDG 7, the financing volume would amount to $40-55 billion annually, with around two thirds going to SSA countries (IEA, 2019a).

5.3.2. SDG 12: Responsible Consumption and Production

Global material extraction and consumption has grown rapidly and the transition towards environmentally friendly consumption and production patterns requires fundamental restructuring of our economy. At its core, SDG 12 emphasizes the general view that material well-being is not a function of resource use as such, but rather arises from its ability to deliver useful goods and services to our society (Creutzig et al., 2018). Resource policies should especially focus on reducing the demand for raw materials, cutting emissions and waste from consumption, and producing and promoting sustainability across every economic sector. The UN (2017) defines the tasks of SDG 12 as follows:

- Implementing the 10-year framework of programs on sustainable consumption and production, all countries taking action, with developed countries taking the lead, taking into account the development and capabilities of developing countries
- Achieving the sustainable management and efficient use of natural resources, by 2030,
- Halve global food waste per capita at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses, by 2030
- Achieving the environmental sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water, and soil, in order to minimize their adverse impacts on human health and the environment, by 2030
- Substantially reducing waste generation through prevention, reduction, recycling, and reuse by 2030,
- Encouraging companies, especially large and transnational companies, to adopt sustainable practices and to integrate sustainability information into their reporting cycle
- Promoting public procurement practices that are sustainable, in accordance with national policies and priorities
- Ensuring that people everywhere have the relevant information and awareness for sustainable development and lifestyles in harmony with nature, by 2030
- Supporting developing countries to strengthen their scientific and technological capacity to move towards more sustainable patterns of consumption and production
- Developing and implement tools to monitor sustainable development impacts for sustainable tourism that creates jobs and promotes local culture and products
- Rationalize inefficient fossil-fuel subsidies that encourage wasteful consumption by removing market distortions in accordance with national circumstances, including

restructuring taxation and phasing out those harmful subsidies where they exist, to reflect their environmental impacts taking fully into account the specific needs and conditions of developing countries, and minimizing the possible adverse impacts on their development in a manner that protects the poor and the affected communities

Dematerialization efforts and policies to reach efficient resource use hitherto barely bear fruits. Society has so far only witnessed growing resource use and there are no signs of decoupling economic development and population growth from material consumption (Schandl and West, 2010). The vague phrasing of the tasks of SDG 12 formulated above, underlines the difficulty to establish a worldwide policy framework for sustainable resource utilization. Consequently, the analysis of SDGs is not straightforward.

5.3.3. SDG 13: Climate Action

Global climate change has recently reached the center of social perception. The urgency to act immediately to prevent catastrophic impacts on natural systems and human well-being has been pronounced by scientists for several decades. The reduction of GHG-emissions and the associated pressure upon the environment is the purpose of SDG 13, so the UN (2017) defines the tasks as:

- Strengthening resilience and adaptive capacity to climate-related hazards and natural disasters in all countries
- Integrating climate change measures into national policies, strategies and planning
- Improving education, awareness-raising, and human and institutional capacity on climate change mitigation, adaptation, impact reduction, and early warning
- Implementing the commitment undertaken by developed-country parties to the United Nations Framework Convention on Climate Change to a goal of mobilizing jointly $100 billion annually by 2020 from all sources, to address the needs of developing countries in the context of meaningful mitigation actions and transparency on implementation and fully operationalize the Green Climate Fund through its capitalization as soon as possible
- Promoting mechanisms for raising capacity for effective climate change-related planning and management in least developed countries and small island developing States, including focusing on women, youth, and local and marginalized communities

Despite the success of action in climate finance and the decline in GHG-emissions in few countries, global emissions are still growing as a consequence of too lax ambitions (IPCC, 2013). National and international efforts to limit global warming to well below 1.5°-2°C before pre-industrial levels require a cut of emissions at much faster rates than currently (UN, 2017). The peak of emission has to be reached as soon as possible with a subsequent sharp decline.

5.3.4. Synergies and Trade-offs

The synergistic accomplishment of SDGs and the related co-benefits are the most optimal pathway for sustainability transformation; however, the realization of such goals could also involve unfavorable trade-offs. A trade-off in this context means that the achievement of a certain goal happens to the expense of another goal.

According to scenario analyses, SDG 12 scores highest regarding synergies to other SDGs. This is attributed to resource efficient practices that often stimulate the conservation of environment natural resources including oceans, biodiversity, and climate. Moreover, SDG 12 liberates resources to people for poverty alleviation and a fair allocation of material well-being. Likewise, SDG 7 brings about co-benefits in the fulfillment of other SDGs, such as alleviation of poverty and malnutrition, improved health care and education, reduced risks and increased gender equality (IIASA, 2018). Conversely, SDG 7 can be detrimental for SDG 12 and SDG 13, as elucidated in the following paragraphs.

A prerequisite to accomplish a set of SDGs is the access to essential amenities and services. This further entails the utilization of resources to derive benefits from the consumption of commodities and services such as clothes, food, and energy. But how can development aspirations of the world´s poor be aligned with responsible resource consumption and planetary boundaries? Of course, overconsumption patterns of the Global North are not a desirable objective for people of the Global South. The fulfillment of SDG 7 requires not only substantial financial investments to expand the electricity infrastructure, but also a significant amount of material extraction to build up the transmission and distribution system. Increasing access to electricity in the Global South can therefore lead to overconsumption patterns of the Global North. SDG 7 sets the goal of universal electricity access by 2030, which involves not only the supply of enough generation capacities, but also the construction of an infrastructure to transmit electricity from generators to consumers. As has been shown throughout this work, the quantity of material stocks incorporated in the existing infrastructure is remarkable, and one can expect growing resource use with the associated establishment of the infrastructure. Scholars have so far widely neglected the increasing material demand for expanding electric power systems and the associated environmental impacts that arise from the production of foremost concrete, steel, copper, and aluminum. The achievement of SDG 7 and SDG 12 may thus stand in contrast to each other, at least with respect to the electricity infrastructure.

I moreover argue that the associated GHG-emitting potential from the manufacturing processes of the employed materials in the infrastructure largely remained neglected in SDG analysis. It has frequently been emphasized, that SDG 7 and SDG 13 are compatible goals, as the provision of clean renewable energy leads to a reduction of GHG-emissions (IIASA, 2018). However, the focus lies on the generation of energy through switching from fossil fuels to RES. The construction of an electricity infrastructure, the related material demand, and GHG-emissions from the manufacturing of those materials are however neglected. The significance of the electricity infrastructure with respect to SDG 13 is highlighted by the fact that various materials that are employed in the transmission and distribution infrastructure are highly energy-intensive in their production processes. In particular the material demand for concrete, steel, aluminum, and copper require large amounts of energy and correspond to over 50% of industrial CO2-emissions (IEA, 2008). Those materials are essential components of conductors, towers, and foundations. Hence the large-scale implementation of an electricity infrastructure that comes with SDG 7 could thus, at least partially, go to the detriment of SDG 13.

Yet there are routes to attenuate resource consumption as a result of increasing electricity access. Particularly SSA countries hold great potential to leapfrog in advanced energy systems, hence the construction of large-scale transmission systems would become obsolete. Small-scale solar PV systems represent cost-efficient opportunities to electrify remote rural areas in the Global South that help to provide affordable electricity to the world´s poor (Pachauri, 2013), and additionally do not need to feed into an interconnected transmission grid. The absence of the establishment of a transmission grid is specifically advantageous to realize SDG 7, SDG12, and SDG 13 simultaneously, since the transmission system is much more material intensive. High material demands of steel-reinforced concrete foundations, steel lattice towers, and aluminum conductors that cover long distances would not have to be employed for millions of people. Instead, citizens could benefit from clean energy on site.

Besides SSA, other parts of the world may also experience high material demand for global transmission infrastructure investments. Several ideas have been proposed to connect electricity grids between large spatial distances, and economists have recently emphasized the emergence of an intercontinental interconnected grid. Many researchers agree to the fact, that a global power grid is a means to harness vast amounts of RES due to the significant operational benefits of an intercontinental power system (Brinkerink et al., 2019). The operational benefits include the smoothening out of the electricity supply and demand, minimizing power reserves, alleviating the storage problem, reducing the volatility of electricity prices, enhancing power system security, and increasing global cooperation with several positive effects on the political and commercial dimensions. Moreover, countries with increasing energy demand and a carbon intensive energy supply and lower RES potential, could benefit from the global interconnections by importing electricity from RES of other countries (Chatzivasileiadis et al., 2013). This will be of vital importance in the implementation of RES, which are not only intermittent in its nature, but also abundant in remote locations such as offshore (wind, tidal) or deserts (PV, solar thermal).

The construction of a global or intercontinental power system has already been subject to several scientific studies. Paris (1992) has evaluated the technical feasibility and economic competitiveness of a large hydro power plant at the Congo River (Inga Dam) in Central Africa and the transmission of the produced power to Italy. From his research, he encourages this idea due to its cost-effectiveness. Moreover, It has been shown that producing electricity from geothermal and hydro power plants in Iceland for the UK electricity market is a realistic option (Hammons et al., 1993, Chatzivasileiadis et al., 2013). RES from Russia could also contribute to accomplish the EU targets to reduce the carbon emissions from the energy sector, while simultaneously begin to develop a national renewable energy industry without risking potential price increases for domestic consumers. This would present a win–win situation for the EU-Russian cooperation. These ideas did not only remain theoretical thoughts of visionaries, they have already been put into concrete actions such as the Baltic Ring, but also other projects were launched to utilize the benefits of an intercontinental power grid (Boute and Willems, 2012).

All those above-mentioned plans require generous investments in the transmission grid. In Germany, additional capacities of 1700–3600 km transmission lines will be necessary to meet the 39% RES target (Ecofys, 2014). The International Energy Agency approximates the length of additional required power lines of 23 million km by 2030, not only due to RES targets, but also to meet increasing electricity demand (IEA, 2012). This should draw attention to growing resource use that is accompanied with RES deployment when implementing GHG-reduction targets. The establishment of a global grid is highly resource intensive and involves substantial material demand that again triggers global warming.

Dematerialization efforts formulated in SDG 12 to reduce material demand thus stand against central pillars of SDG 7, such as “to ensure universal access to affordable, reliable and modern energy services” and “increase substantially the share of renewable energy in the global energy mix”, by 2030. Although the realization of SDG 7 and SDG 13 is considered as a synergistic achievement, this only holds for energy generation. Energy transmission and distribution involves, however, the use of carbon intensive materials, hence the realization of SDG 7 and SDG 13 is not fully synergistic.

6. Conclusion

This work has quantified material stocks in the global electricity infrastructure. From a social metabolism perspective ("stock-flow-service nexus", see Haberl et al. (2017)) these stocks are crucial for providing energy, services, and amenities. Furthermore, this work evaluated the spatial distribution of material stocks through a methodical combination of using GIS data and multiple regression analysis and conducted a scenario to estimate future stocks.

The material in-use stocks incorporated in the global electricity transmission and distribution infrastructure amount to 2184 ± 366 Mt in total, with the global high voltage transmission system accounting to 663 Mt. Material stocks within Eurelectric member states add up to around 295 ± 28 Mt. The low-, and medium voltage distribution system contains with 165 ± 37 Mt significant quantities of copper, corresponding to 32-59 % of total in-use stocks. Total per capita stocks are at around 288 ± 48 kg per capita and range from 69 kg per capita in Congo, Dem. Rep., or Malawi, to 1541 kg per capita in Finland. The major driver of total material demand is concrete with approximately 145 ± 47 kg per capita. Overall, the entire material stock might increase by 34 Mt annually until the year 2030 (from 2018) and could amount to about 2500 Mt by 2030 and 2800 Mt by 2050.

Rising access to electricity, especially in SSA, along with global population growth, is a key driver of material consumption. High RES deployment to reach GHG-reduction targets will further contribute to the material accumulation, especially the transmission system which is highly resource intensive. Options to reduce material demand include the employment of off-grid and mini-grid PV system that would make the construction of transmission systems in rural SSA obsolete. Additionally, hibernating copper stocks could be cost-efficiently used if combined with maintenance work on the grid and, thus, mitigate copper scarcity to some extent. Particularly increased recycling rates of materials in underground systems are relevant for recovering secondary materials from the electricity infrastructure.

Scholars and policymakers should thus not neglect the accompanied growing resource demand of electricity transmission and distribution and take action to reduce the associated environmental impacts. Further measures are required to achieve sustainable development within planetary boundaries, such as the increase of recycling rates and awareness on electricity infrastructure related environmental impacts. At first glimpse, SDG 7 ("Affordable and Clean Energy") and SDG 12 ("Responsible Resource Consumption and Production"), as well as SDG 7 and SDG 13 ("Climate Action") seem to be competitive goals, however, the synergistic realization is feasible if more effort is put on dematerialization in the energy sector.

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Appendix A

Countries and their assignment to continents in this work. Countries marked in bold letters are Eurelectric member states.

Europe	North America	Asia	Latin America	Africa	Oceania
Albania	United States	Bahrain	Argentina	Algeria	Australia
Armenia	Canada	Bangladesh	Bolivia	Angola	New Zealand
Austria		Brunei Darussalam	Brazil	Botswana	
Azerbaijan		Cambodia	Chile	Cameroon	
Belarus		Iran, Islamic Rep.	Colombia	Congo, Dem. Rep.	
Belgium		Iraq	Costa Rica	Congo, Rep.	
Bosnia and Herzegovina		Japan	Cuba	Cote d'Ivoire	
Bulgaria		Jordan	Dominican Republic	Egypt, Arab Rep.	
Croatia		Kazakhstan	Ecuador	Ethiopia	
Cyprus		Korea, North	El Salvador	Gabon	
Czech Republic		Korea, South	Guatemala	Ghana	
Denmark		Kuwait	Haiti	Kenya	
Estonia		Kyrgyz Republic	Honduras	Libya	
Finland		Malaysia	Jamaica	Mauritius	
France		Mongolia	Mexico	Morocco	
Georgia		Myanmar	Nicaragua	Mozambique	
Germany		Nepal	Panama	Namibia	
Gibraltar		Oman	Paraguay	Niger	
Greece		Pakistan	Peru	Nigeria	
Hungary		Philippines	Trinidad and Tobago	Senegal	
Iceland		Qatar	Uruguay	South Africa	
Ireland		Saudi Arabia	Venezuela, RB	South Sudan	
Israel		Sri Lanka		Sudan	
Italy		Syrian Arab Republic		Suriname	
Kosovo		Tajikistan		Tanzania	
Latvia		Thailand		Togo	
Lithuania		Turkmenistan		Tunisia	
Luxembourg		United Arab Emirates		Zambia	
Malta		Uzbekistan		Zimbabwe	
Moldova		Vietnam			
Montenegro		Yemen, Rep.			
Netherlands					
North Macedonia					
Norway					
Poland					
Portugal					
Romania					
Serbia					
Slovak Republic					
Slovenia					
Spain					
Sweden					
Switzerland					
Turkey					
Ukraine					
United Kingdom					

Appendix B

Line lengths (in km) of regression results. Countries marked in bold letters are Eurelectric member states

Country	Line length
Afghanistan	699020
Albania	168588
Algeria	503038
Andorra	27163
Angola	228082
Antigua and Barbuda	7309
Argentina	528026
Armenia	168691
Australia	336023
Austria	**235600**
Azerbaijan	241461
Bahamas, The	80420
Bahrain	892575
Bangladesh	1946227
Belarus	208642
Belgium	**193165**
Belize	88439
Benin	136220
Bhutan	93672
Bolivia	201298
Bosnia and Herzegovina	157177
Botswana	113289
Brazil	2104928
British Virgin Islands	13630
Brunei Darussalam	65046
Bulgaria	192840
Burkina Faso	148578
Cabo Verde	46281
Cambodia	272206
Cameroon	264400
Canada	737870
Central African Republic	109880
Chad	112699
Chile	285914
China	13475927
Colombia	584136
Congo, Dem. Rep.	262276
Congo, Rep.	136985
Costa Rica	185126
Cote d'Ivoire	283683
Croatia	167951
Cuba	251591
Cyprus	**161577**
Czech Republic	**221441**
Denmark	**171819**
Djibouti	82759
Dominica	53148
Dominican Republic	287758
Ecuador	287084
Egypt, Arab Rep.	1064160
El Salvador	284647
Equatorial Guinea	86120
Estonia	60000
Eswatini	77985
Ethiopia	594383
Faroe Islands	75815
Fiji	84866
Finland	**382740**
France	**1293466**
French Polynesia	64344
Gabon	119941
Gambia, The	27066
Georgia	160697
Germany	**1772696**
Ghana	371365
Greece	**229877**
Greenland	89075
Guatemala	314076
Guinea	145669
Guinea-Bissau	71877
Guyana	99183
Haiti	306374
Honduras	210968
Hungary	**161954**
Iceland	103091
India	12436852
Indonesia	996101
Iran, Islamic Rep.	893460
Iraq	494255
Ireland	**167528**
Isle of Man	33813
Israel	345604
Italy	**1105216**
Jamaica	235838
Japan	1457515
Jordan	237068
Kazakhstan	274383
Kenya	442074
Kiribati	36509
Korea, North	291329
Korea, South	807153
Kosovo	184270
Kuwait	229792
Kyrgyz Republic	171063
Lao PDR	192659
Latvia	**93764**
Lebanon	434227
Lesotho	74489
Liberia	87561
Libya	144263
Lithuania	**123749**
Luxembourg	**8477**
Madagascar	181128
Malawi	56813
Malaysia	435637
Mali	224530
Malta	696776
Mauritania	119300
Mauritius	363277
Mexico	1323063
Micronesia, Fed. Sts.	29147
Moldova	182699
Mongolia	124899
Montenegro	123170
Morocco	472565
Mozambique	188670
Myanmar	489595
Namibia	111703

Nepal	430122
Netherlands	**252634**
New Caledonia	87288
New Zealand	151844
Nicaragua	173163
Niger	146916
Nigeria	1180932
North Macedonia	151923
Northern Mariana Islands	42350
Norway	**128591**
Oman	149343
Pakistan	1621613
Palau	73714
Panama	160283
Papua New Guinea	162893
Paraguay	170922
Peru	399442
Philippines	1181198
Poland	**774141**
Portugal	**222627**
Qatar	219875
Romania	**89944**
Russian Federation	1490004
Samoa	65232
Sao Tome and Principe	8726
Saudi Arabia	422600
Senegal	222311
Serbia	198440
Seychelles	10559
Sierra Leone	79884
Slovak Republic	**91353**
Slovenia	**63120**
Solomon Islands	86610
Somalia	164948
South Africa	579606
South Sudan	125004
Spain	**695427**
Sri Lanka	438191
St. Kitts and Nevis	12891
Sudan	319719
Suriname	105190
Sweden	**528606**
Switzerland	266441
Syrian Arab Republic	283111
Tajikistan	209089
Tanzania	295762
Thailand	818234
Timor-Leste	74126
Togo	191374
Tonga	36006
Trinidad and Tobago	10141
Tunisia	238114
Turkey	920248
Turkmenistan	158684
Turks and Caicos Islands	73923
Uganda	171425
Ukraine	560470
United Arab Emirates	243779
United Kingdom	**837156**
United States	9700000
Uruguay	139387
Uzbekistan	440440
Vanuatu	82410
Venezuela, RB	394253
Vietnam	1130971
Yemen, Rep.	331573
Zambia	172851
Zimbabwe	168624

Appendix C

Line length (in km) of continents and subdivided in 1 kV and 1-100 kV distribution system

	1-100 kV			< 1 kV		
	Total	**OH**	**UG**	**Total**	**OH**	**UG**
World	95589170					
low	34354127	19510851	9135009	53483736	24048090	20038668
mid	37270434	24394254	12876181	56286404	29974428	26454276
high	40186741	29277656	16617352	59089071	35900765	32869884
Europe						
Total	15597942					
low	5605799	3183720	1490622	8727309	3924092	3269847
mid	6081673	3980578	2101095	9184640	4891134	4316726
high	6557547	4777436	2711568	9641970	5858175	5363605
North America						
Total	10426035					
low	3747049	2128074	996367	5833540	2622956	2185644
mid	4065135	2660713	1404422	6139231	3269350	2885402
high	4383220	3193352	1812476	6444922	3915743	3585161
Asia						
Total	46865223					
low	16843057	9565732	4478690	26221875	11790238	9824509
mid	18272857	11959955	6312902	27595960	14695789	12969937
high	19702657	14354177	8147114	28970044	17601339	16115366
Latin America						
Total	9372548					
low	3368433	1913045	895691	5244097	2357923	1964798
mid	3654378	2391864	1262514	5518900	2939002	2593850
high	3940323	2870683	1629337	5793702	3520081	3222902
Africa						
Total	11914010					
low	4281818	2431787	1138566	6666088	2997298	2497573
mid	4645300	3040443	1604857	7015406	3735942	3297199
high	5008781	3649098	2071148	7364723	4474587	4096825
Oceania						
Total	1176344					
low	422770	240105	112418	658184	295942	246601
mid	458659	300202	158457	692674	368873	325553
high	494548	360298	204497	727164	441804	404505

Appendix D

Material stocks of the low voltage (< 1kV) system by continent in Mt

	Material	World low	World mid	World high	Europe low	Europe mid	Europe high	North America low	North America mid	North America high
OH										
Line + Insulation	Copper	32.5	40.5	48.5	5.6	7.0	8.4	3.7	4.6	5.6
	Steel	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Lead	48.2	60.1	72.0	8.4	10.4	12.5	5.5	6.9	8.2
	PVC	23.0	28.6	34.3	4.0	5.0	5.9	2.6	3.3	3.9
	Paper	10.3	12.9	15.4	1.8	2.2	2.7	1.2	1.5	1.8
	Mineral oil	9.2	11.5	13.7	1.6	2.0	2.4	1.1	1.3	1.6
Masts	Timber	119.5	148.9	178.4	20.7	25.8	30.9	13.7	17.0	20.4
	Total	242.7	302.5	362.4	42.0	52.4	62.7	27.8	34.6	41.5
UG										
Line + Insulation	Copper	27.1	35.7	44.4	4.7	6.2	7.7	3.1	4.1	5.1
	Steel	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Lead	40.2	53.1	65.9	7.0	9.2	11.4	4.6	6.1	7.5
	PVC	19.1	25.3	31.4	3.3	4.4	5.4	2.2	2.9	3.6
	Paper	8.6	11.4	14.1	1.5	2.0	2.4	1.0	1.3	1.6
	Mineral oil	7.7	10.1	12.6	1.3	1.8	2.2	0.9	1.2	1.4
Cable duct	Steel	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Concrete	328.0	433.0	538.1	56.8	75.0	93.1	37.5	49.6	61.6
	Resins	0.5	0.6	0.8	0.1	0.1	0.1	0.1	0.1	0.1
	Plastics	0.5	0.6	0.8	0.1	0.1	0.1	0.1	0.1	0.1
	Total	431.7	569.9	708.1	74.7	98.7	122.6	49.4	65.2	81.0

	Material	Asia low	Asia mid	Asia high	Latin America low	Latin America mid	Latin America high	Africa low	Africa mid	Africa high	Oceania low	Oceania mid	Oceania high
OH													
Line + Insulation	Copper	17.0	21.2	25.4	3.3	4.1	4.9	3.5	4.3	5.2	0.3	0.4	0.5
	Steel	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Lead	25.3	31.5	37.8	4.9	6.1	7.3	5.1	6.4	7.7	0.5	0.6	0.7
	PVC	12.0	15.0	18.0	2.3	2.9	3.5	2.4	3.0	3.6	0.2	0.3	0.3
	Paper	5.4	6.8	8.1	1.1	1.3	1.6	1.1	1.4	1.6	0.1	0.1	0.1
	Mineral oil	4.8	6.0	7.2	0.9	1.2	1.4	1.0	1.2	1.5	0.1	0.1	0.1
Masts	Timber	62.6	78.1	93.5	12.2	15.2	18.2	12.7	15.8	19.0	1.1	1.4	1.7
	Total	127.3	158.6	190.0	24.8	30.9	37.0	25.8	32.2	38.5	2.3	2.9	3.4
UG													
Line + Insulation	Copper	14.2	18.7	23.3	2.8	3.6	4.5	2.9	3.8	4.7	0.3	0.3	0.4
	Steel	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Lead	21.1	27.8	34.6	4.1	5.4	6.7	4.3	5.6	7.0	0.4	0.5	0.6
	PVC	10.0	13.3	16.5	2.0	2.6	3.2	2.0	2.7	3.3	0.2	0.2	0.3
	Paper	4.5	6.0	7.4	0.9	1.2	1.4	0.9	1.2	1.5	0.1	0.1	0.1
	Mineral oil	4.0	5.3	6.6	0.8	1.0	1.3	0.8	1.1	1.3	0.1	0.1	0.1
Cable duct	Steel	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Concrete	172.0	227.1	282.1	33.5	44.2	54.9	34.9	46.1	57.2	3.1	4.1	5.1
	Resins	0.3	0.3	0.4	0.0	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0
	Plastics	0.3	0.3	0.4	0.0	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0
	Total	226.4	298.8	371.3	44.0	58.1	72.3	45.9	60.6	75.3	4.1	5.4	6.7

Appendix E

Material stocks of the medium voltage (1-100 kV) system by continent in Mt.

	Material	World low	World mid	World high	Europe low	Europe mid	Europe high	North America low	North America mid	North America high
OH										
Cables	Copper	43.4	54.3	65.2	7.5	9.4	11.3	5.0	6.2	7.5
	Aluminium	17.5	21.9	26.3	3.0	3.8	4.6	2.0	2.5	3.0
Insulation	PE	0.5	0.7	0.8	0.1	0.1	0.1	0.1	0.1	0.1
	Silicon rubber	0.3	0.3	0.4	0.0	0.1	0.1	0.0	0.0	0.0
	Steel	17.2	21.5	25.8	3.0	3.7	4.5	2.0	2.5	3.0
	Porcelain	1.2	1.6	1.9	0.2	0.3	0.3	0.1	0.2	0.2
Masts	Timber	100.6	125.7	150.9	17.4	21.8	26.1	11.5	14.4	17.3
	Total	180.8	226.0	271.3	31.3	39.1	47.0	20.7	25.9	31.0
UG										
Cables	Copper	24.3	34.2	44.2	4.2	5.9	7.7	2.8	3.9	5.1
	Aluminium	24.0	33.9	43.7	4.2	5.9	7.6	2.8	3.9	5.0
	PET	17.3	24.3	31.4	3.0	4.2	5.4	2.0	2.8	3.6
	EPR	3.2	4.5	5.8	0.5	0.8	1.0	0.4	0.5	0.7
Cable duct	Steel	0.2	0.3	0.3	0.0	0.0	0.1	0.0	0.0	0.0
	Resins	0.2	0.3	0.4	0.0	0.1	0.1	0.0	0.0	0.0
	Plastics	0.2	0.3	0.4	0.0	0.1	0.1	0.0	0.0	0.0
	Concrete	230.4	324.8	419.1	39.9	56.2	72.6	26.4	37.2	48.0
	Total	299.8	422.6	545.3	51.9	73.1	94.4	34.3	48.4	62.4

	Material	Asia low	Asia mid	Asia high	Latin America low	Latin America mid	Latin America high	Africa low	Africa mid	Africa high	Oceania low	Oceania mid	Oceania high
OH													
Cables	Copper	22.8	28.5	34.2	4.4	5.5	6.6	4.6	5.8	6.9	0.4	0.5	0.6
	Aluminium	9.2	11.5	13.8	1.8	2.2	2.7	1.9	2.3	2.8	0.2	0.2	0.2
Insulation	PE	0.3	0.3	0.4	0.1	0.1	0.1	0.1	0.1	0.1	0	0	0
	Silicon rubber	0.1	0.2	0.2	0	0	0	0	0	0	0	0	0
	Steel	9	11.3	13.5	1.8	2.2	2.6	1.8	2.3	2.7	0.2	0.2	0.2
	Porcelain	0.7	0.8	1	0.1	0.2	0.2	0.1	0.2	0.2	0	0	0
Masts	Timber	52.7	65.9	79.1	10.3	12.8	15.4	10.7	13.4	16	1	1.2	1.4
	Total	94.8	118.5	142.2	18.4	23.1	27.7	19.2	24	28.8	1.7	2.1	2.6
UG													
Cables	Copper	12.7	18	23.2	2.5	3.5	4.5	2.6	3.6	4.7	0.2	0.3	0.4
	Aluminium	12.6	17.8	22.9	2.5	3.5	4.5	2.6	3.6	4.6	0.2	0.3	0.4
	PET	9.1	12.8	16.5	1.8	2.5	3.2	1.8	2.6	3.3	0.2	0.2	0.3
	EPR	1.7	2.3	3	0.3	0.5	0.6	0.3	0.5	0.6	0	0	0.1
Cable duct	Steel	0.1	0.1	0.2	0	0	0	0	0	0	0	0	0
	Resins	0.1	0.2	0.2	0	0	0	0	0	0	0	0	0
	Plastics	0.1	0.2	0.2	0	0	0	0	0	0	0	0	0
	Concrete	120.8	170.3	219.8	23.5	33.1	42.8	24.5	34.5	44.6	2.2	3.1	4
	Total	157.2	221.6	285.9	30.6	43.1	55.6	31.9	44.9	58	2.9	4	5.2

Appendix F

Material stocks of the high voltage (>100 kV) transmission system by continent in Mt.

	World	Europe	North America	Asia	Latin America	Africa	Oceania
OH							
Concrete	450.1	107.1	77.2	175.1	57.2	37.2	7.3
Iron	21.9	5.1	3.7	8.7	2.8	1.8	0.3
Steel	71.1	16.4	11.8	28.6	9.3	5.8	1.0
Zinc	1.5	0.3	0.2	0.6	0.2	0.1	0.0
Hard glass	2.0	0.5	0.3	0.8	0.3	0.2	0.0
Steel	2.3	0.6	0.4	0.8	0.3	0.2	0.0
Cement	0.1	0.0	0.0	0.1	0.0	0.0	0.0
Steel	8.0	2.0	1.4	3.0	1.0	0.7	0.1
Aluminium	22.0	5.4	3.9	8.3	2.7	1.8	0.4
Mineral fat	1.2	0.3	0.2	0.4	0.1	0.1	0.0
Steel	1.5	0.4	0.3	0.6	0.2	0.1	0.0
Aluminium	0.9	0.2	0.2	0.4	0.1	0.1	0.0
Mineral fat	0.0	0.0	0.0	0.0	0.0	0.0	0.0
UG							
Copper	0.3	0.3	0.0	0.0	0.0	0.0	0.0
Paper	0.1	0.1	0.0	0.0	0.0	0.0	0.0
Insulation oil	0.2	0.1	0.0	0.0	0.0	0.0	0.0
Lead	0.5	0.5	0.0	0.0	0.0	0.0	0.0
Bronze	0.1	0.1	0.0	0.0	0.0	0.0	0.0
Asphalt	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PP	0.1	0.1	0.0	0.0	0.0	0.0	0.0
Sand	60.5	55.7	1.3	0.8	1.6	0.3	1.2
Concrete	1.3	1.2	0.0	0.0	0.0	0.0	0.0
Asphalt	2.8	2.6	0.1	0.0	0.1	0.0	0.1

Appendix G

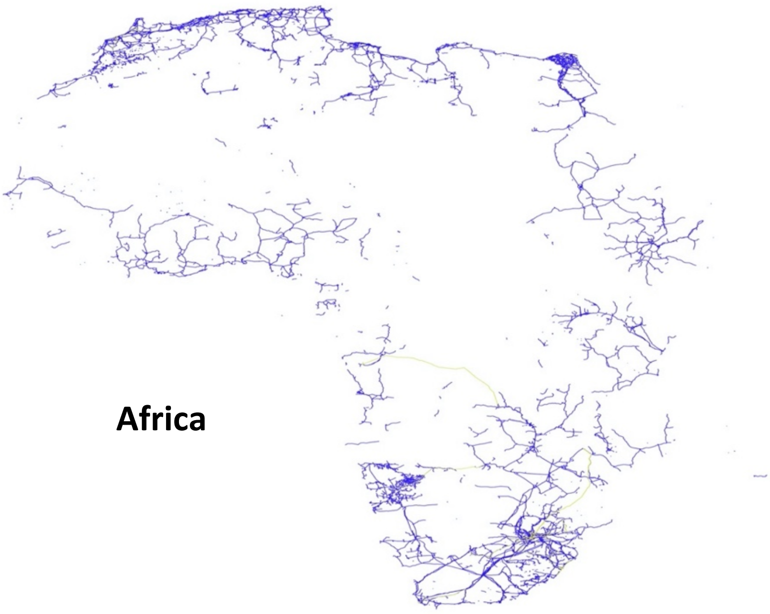
Historic and projected future development of material stocks. Values are presented in Mt.

Year	Line length (km)	Concrete	Timber	Copper	Steel	Lead	Aluminum	Plastics	Paper	Mineral oil	Porcelain	Zinc	Asphalt	Sand	Total
2000	73305624	930	220	135	87	94	62	68	20	19	4	0	18	60	1638
2001	73720213	936	222	136	88	95	63	69	21	20	4	0	18	61	1647
2002	75274651	955	226	139	89	97	64	70	21	20	4	0	19	62	1682
2003	76248646	968	229	141	91	98	65	71	21	20	4	1	19	63	1704
2004	76961535	977	231	142	91	99	66	72	21	20	4	1	19	64	1720
2005	77819264	988	234	143	92	100	66	72	22	21	4	1	19	64	1739
2006	79061978	1003	238	146	94	102	67	73	22	21	4	1	20	65	1767
2007	80378724	1020	242	148	95	103	68	75	22	21	4	1	20	66	1796
2008	80987851	1028	244	149	96	104	69	75	23	22	4	1	20	67	1810
2009	82187783	1043	247	152	98	106	70	76	23	22	4	1	21	68	1837
2010	83135016	1055	250	153	99	107	71	77	23	22	4	1	21	69	1858
2011	83021235	1054	250	153	99	107	71	77	23	22	4	1	21	69	1855
2012	85574115	1086	257	158	102	110	73	80	24	23	4	1	21	71	1912
2013	86520936	1098	260	159	103	111	74	80	24	23	4	1	22	71	1933
2014	87537585	1111	263	161	104	113	75	81	24	23	4	1	22	72	1956
2015	89234785	1132	268	164	106	115	76	83	25	24	4	1	22	74	1994
2016	90803546	1152	273	167	108	117	77	84	25	24	5	1	23	75	2029
2017	92231922	1170	277	170	110	119	79	86	26	25	5	1	23	76	2061
2018	94061425	1194	283	173	112	121	80	87	26	25	5	1	24	78	2102
2019	94810684	1203	285	175	113	122	81	88	26	25	5	1	24	78	2119
2020	97890491	1242	294	180	116	126	83	91	27	26	5	1	25	81	2187
2021	98647472	1252	297	182	117	127	84	92	27	26	5	1	25	81	2204
2022	99395197	1261	299	183	118	128	85	92	28	26	5	1	25	82	2221
2023	100133592	1271	301	185	119	129	85	93	28	27	5	1	25	83	2238
2024	100862777	1280	303	186	120	130	86	94	28	27	5	1	25	83	2254
2025	106188795	1348	319	196	126	137	90	99	30	28	5	1	27	88	2373
2026	106941789	1357	322	197	127	137	91	99	30	28	5	1	27	88	2390
2027	107684709	1367	324	199	128	138	92	100	30	29	5	1	27	89	2406
2028	108417673	1376	326	200	129	139	92	101	30	29	5	1	27	89	2423
2029	109140894	1385	328	201	130	140	93	101	30	29	5	1	27	90	2439
2030	112561097	1428	339	207	134	145	96	105	31	30	6	1	28	93	2515
2031	113287392	1438	341	209	135	146	96	105	32	30	6	1	28	93	2531
2032	114003763	1447	343	210	135	147	97	106	32	30	6	1	29	94	2547
2033	114710224	1456	345	211	136	147	98	107	32	31	6	1	29	95	2563
2034	115406786	1464	347	213	137	148	98	107	32	31	6	1	29	95	2579
2035	116093456	1473	349	214	138	149	99	108	32	31	6	1	29	96	2594
2036	116770181	1482	351	215	139	150	99	109	32	31	6	1	29	96	2609
2037	117436962	1490	353	216	139	151	100	109	33	31	6	1	29	97	2624
2038	118093920	1499	355	218	140	152	101	110	33	31	6	1	30	97	2639
2039	118741219	1507	357	219	141	153	101	110	33	32	6	1	30	98	2653
2040	119378934	1515	359	220	142	153	102	111	33	32	6	1	30	99	2668
2041	120007060	1523	361	221	142	154	102	112	33	32	6	1	30	99	2682
2042	120625425	1531	363	222	143	155	103	112	34	32	6	1	30	100	2695
2043	121233730	1538	365	223	144	156	103	113	34	32	6	1	30	100	2709
2044	121831575	1546	366	225	145	157	104	113	34	32	6	1	30	101	2722
2045	122418622	1553	368	226	145	157	104	114	34	33	6	1	31	101	2735
2046	122994755	1561	370	227	146	158	105	114	34	33	6	1	31	101	2748
2047	123559888	1568	372	228	147	159	105	115	34	33	6	1	31	102	2761
2048	124113765	1575	373	229	147	160	106	115	35	33	6	1	31	102	2773
2049	124656104	1582	375	230	148	160	106	116	35	33	6	1	31	103	2785

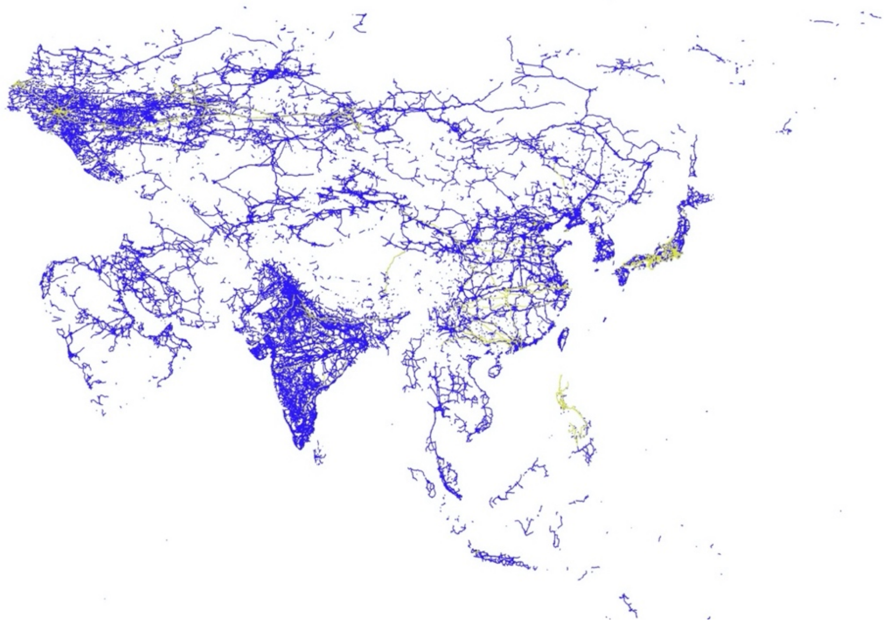
2050	125186696	1589	376	231	149	161	107	116	35	33	6	1	31	103	2797
2051	125705492	1595	378	232	149	162	107	117	35	33	6	1	31	104	2809
2052	126212501	1602	380	233	150	162	107	117	35	34	6	1	32	104	2820
2053	126707669	1608	381	234	150	163	108	118	35	34	6	1	32	105	2831
2054	127190959	1614	383	234	151	164	108	118	35	34	6	1	32	105	2842
2055	127662413	1620	384	235	152	164	109	119	36	34	6	1	32	105	2853
2056	128122061	1626	385	236	152	165	109	119	36	34	6	1	32	106	2863
2057	128570105	1632	387	237	153	165	109	119	36	34	6	1	32	106	2873
2058	129006972	1637	388	238	153	166	110	120	36	34	6	1	32	106	2883
2059	129433220	1642	389	239	154	166	110	120	36	34	6	1	32	107	2892
2060	129849321	1648	391	239	154	167	111	121	36	35	6	1	33	107	2902
2061	130255507	1653	392	240	155	167	111	121	36	35	6	1	33	107	2911
2062	130651928	1658	393	241	155	168	111	121	36	35	6	1	33	108	2919
2063	131038901	1663	394	242	156	168	112	122	36	35	7	1	33	108	2928
2064	131416745	1668	395	242	156	169	112	122	37	35	7	1	33	108	2937
2065	131785737	1672	396	243	156	169	112	122	37	35	7	1	33	109	2945
2066	132146091	1677	397	244	157	170	113	123	37	35	7	1	33	109	2953
2067	132497944	1681	398	244	157	170	113	123	37	35	7	1	33	109	2961
2068	132841383	1686	400	245	158	171	113	123	37	35	7	1	33	110	2968
2069	133176441	1690	401	245	158	171	113	124	37	35	7	1	33	110	2976
2070	133503164	1694	401	246	159	172	114	124	37	36	7	1	33	110	2983
2071	133821683	1698	402	247	159	172	114	124	37	36	7	1	33	110	2990
2072	134132106	1702	403	247	159	172	114	125	37	36	7	1	34	111	2997
2073	134434420	1706	404	248	160	173	114	125	37	36	7	1	34	111	3004
2074	134728568	1710	405	248	160	173	115	125	37	36	7	1	34	111	3011
2075	135014536	1713	406	249	160	174	115	125	38	36	7	1	34	111	3017
2076	135292387	1717	407	249	161	174	115	126	38	36	7	1	34	112	3023
2077	135562254	1720	408	250	161	174	115	126	38	36	7	1	34	112	3029
2078	135824282	1724	408	250	161	175	116	126	38	36	7	1	34	112	3035
2079	136078651	1727	409	251	162	175	116	126	38	36	7	1	34	112	3041
2080	136325525	1730	410	251	162	175	116	127	38	36	7	1	34	112	3046
2081	136564977	1733	411	252	162	176	116	127	38	36	7	1	34	113	3052
2082	136797092	1736	411	252	162	176	117	127	38	36	7	1	34	113	3057
2083	137022075	1739	412	253	163	176	117	127	38	36	7	1	34	113	3062
2084	137240154	1742	413	253	163	176	117	128	38	37	7	1	34	113	3067
2085	137451500	1744	413	253	163	177	117	128	38	37	7	1	34	113	3071
2086	137656199	1747	414	254	163	177	117	128	38	37	7	1	34	114	3076
2087	137854244	1749	415	254	164	177	117	128	38	37	7	1	35	114	3080
2088	138045624	1752	415	254	164	177	118	128	38	37	7	1	35	114	3085
2089	138230286	1754	416	255	164	178	118	128	38	37	7	1	35	114	3089
2090	138408170	1756	416	255	164	178	118	129	39	37	7	1	35	114	3093
2091	138579226	1759	417	255	165	178	118	129	39	37	7	1	35	114	3097
2092	138743405	1761	417	256	165	178	118	129	39	37	7	1	35	114	3100
2093	138900656	1763	418	256	165	179	118	129	39	37	7	1	35	115	3104
2094	139050903	1765	418	256	165	179	118	129	39	37	7	1	35	115	3107
2095	139194049	1766	419	257	165	179	119	129	39	37	7	1	35	115	3110
2096	139329960	1768	419	257	165	179	119	129	39	37	7	1	35	115	3113
2097	139458472	1770	419	257	166	179	119	130	39	37	7	1	35	115	3116
2098	139579384	1771	420	257	166	179	119	130	39	37	7	1	35	115	3119
2099	139692463	1773	420	258	166	180	119	130	39	37	7	1	35	115	3121
2100	139817175	1774	420	258	166	180	119	130	39	37	7	1	35	115	3124

Appendix H

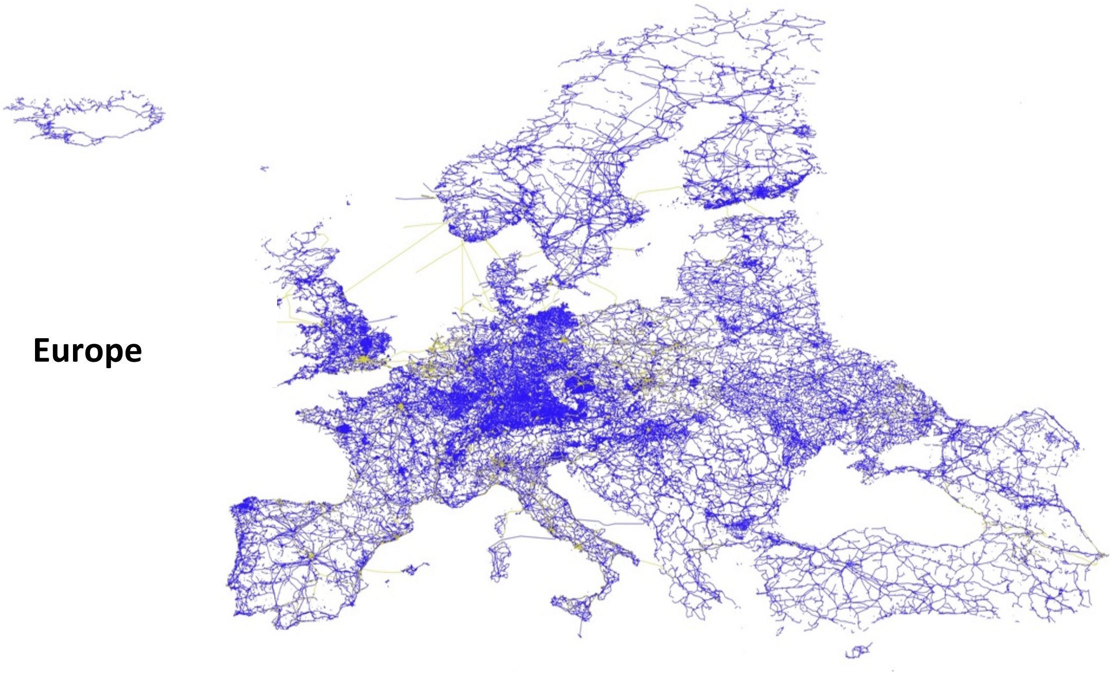
Map of GIS data by continents. Blue lines indicate AC lines, yellow lines DC lines. Lines are >100



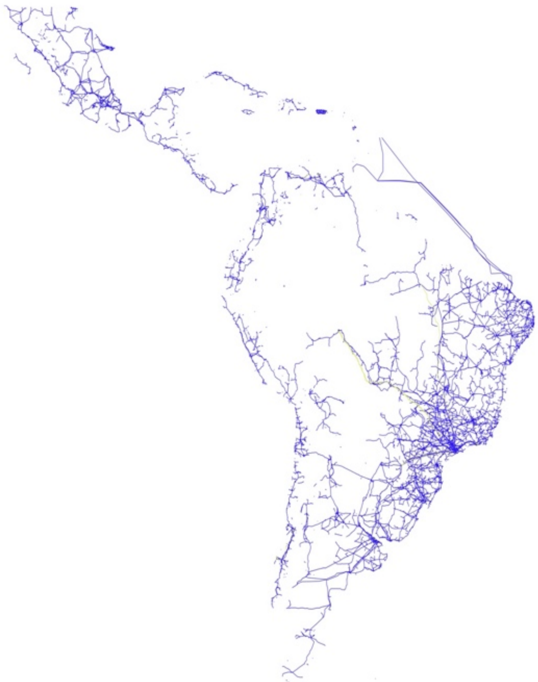
Africa



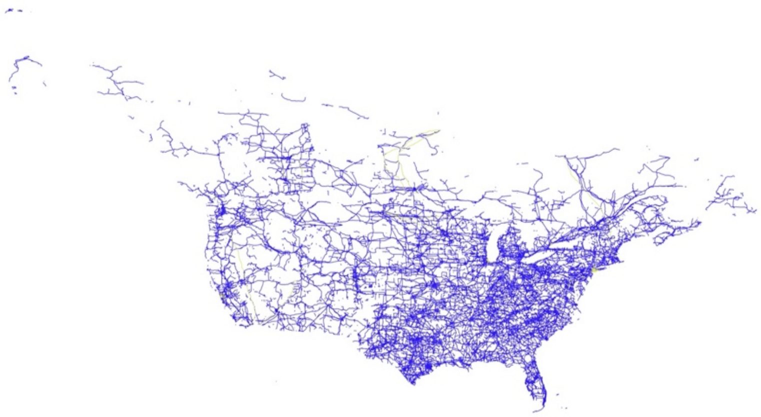
Asia



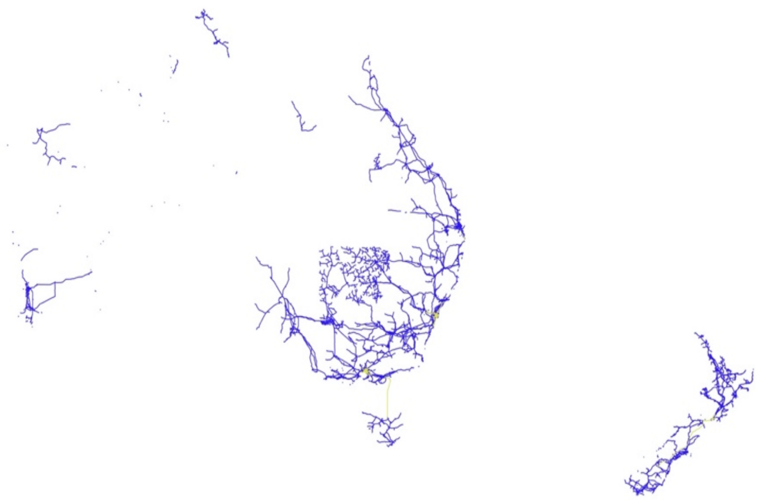
Europe



Latin America



North America



Oceania

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