Investigating the Sustainability of the 5G Base Station Overhaul in the United States

Zesen Zhang[§]
University of California San Diego
zez003@ucsd.edu

Leila Scola[§]
University of California San Diego
lscola@ucsd.edu

Aaron Schulman
University of California San Diego
schulman@cs.ucsd.edu

***Abstract*—5G is a high-bandwidth low-latency communication technology that requires deploying new cellular base stations. The environmental cost of deploying a 5G cellular network remains unknown. In this work we answer several questions about the environmental impact of 5G deployment, including: Can we reuse minerals from discarded 4G base stations to build 5G or does 5G require new minerals that were not required in 4G base stations? And, how sustainable is this transition? We answered these questions buy surveying the minerals needed to build 5G base stations. We found that the key technologies behind 5G require additional rare-earth metals to build essential semiconductor components needed for 5G, such as yttrium, barium, gallium, and germanium. Additionally, since 5G needs many more base stations than 4G network to achieve the same coverage, we describe how 5G will likely increase the use of materials like copper, gold, and aluminum, all of which are difficult or impractical to recycle from the 4G base stations they will replace. We estimate that to provide coverage comparable to 4G in the United States, we will need about 600 million 5G base stations, which will consume thousands of tons of these metals and significant amount of fossil fuels, as well as will result in releasing toxic gases during material mining and refining. Despite these environment costs, we also describe the environmental benefits that a 5G network can offer.**

***Index Terms*—5G, wireless, base station, material**

I. INTRODUCTION

5G is the next generation of wireless communication technology that will significantly improve network bandwidth and decrease latency. There are two key wireless communication technologies in 5G that will bring on these improvements: millimeter-wave wireless communication and massive MIMO (Multiple Input, Multiple Output) antenna arrays [1], [8]. Unfortunately, existing 4G base stations can not be retrofitted to include these technologies; therefore, 5G will require a build out of new base station infrastructure to replace 4G base stations. Also, 5G will require more base stations than 4G/LTE, because the millimeter-wave signals have significantly shorter range than the centimeter-wave signals they are augmenting.

The deployment of 5G may not be sustainable because it requires materials that are increasingly difficult to obtain. For instance, copper is one of the primary materials needed for 5G base stations, but we have already used over half of the copper that can be extracted from nature [51]. These rare materials are not only difficult to mine, but also difficult to recycle. In the near future it will be more economical to recycle than mine ores of these materials [51], [53]. Under this restricted circumstance, the environmental cost of spreading 5G base station remains uncertain.

5G infrastructure also requires one or more new materials that were unneeded in 4G networks. Given that these materials are rare and problematic to mine, they pose a greater environmental threat than more common materials used in 4G electronics like copper, gold, and aluminum. To compound the issue, at best we see 30% of minerals and metal materials in base station get recycled, but that does not mean they are reused [49], [50], [53]. Recycling base station material is difficult because it is covered with epoxies that make it more economical to scrap than to salvage, or the materials are mixed into alloys or delicate parts that are difficult to recycle. These materials will never go back into nature. Additionally, 5G's reduced coverage area will require more base stations, and therefore more of even the most standard minerals than we ever have had for any previous cellular technology overhaul.

In this work, we investigate the environmental impact of the materials needed to deploy 5G. First, we investigate what materials are needed to provide the key functionality introduced in 5G. Then we estimate the total usage of each material in base stations. At the end, we discuss the environmental tradeoffs the 5G base station overhaul. To our best knowledge, this is the first attempt looking into the environmental cost of sourcing materials required to build 5G base stations. Our goal is provide a ballpark estimate of the environmental effect of material management in 5G deployments to help shape future policy around base station overhauls using empirical data.

Specifically, we focus on examining the amount of metal materials required to upgrade U.S. base stations from 4G/LTE to 5G. These metals are used in major 5G base station components such as antennas, filters, power amplifiers and Printed Circuit Boards (PCB). The metals used in these components include: aluminum, gallium, germanium, yttrium, barium, gold, and copper.

Since there are no publicly available statistics about the amounts of these materials used in base stations, we use various techniques to estimate the amount of material in one base station. Then we use k-center approximation algorithm, with data on existing 4G base station deployments from OpenCellID [20], to estimate the total number of 5G base stations required for to provide a nationwide 5G network in the U.S. We then combine the estimates of materials with

---

[§] These two authors contribute equally to this paper.

the estimate of number of base stations needed to provide an estimate of the total amount of materials that will be used to build a nationwide deployment of 5G in the United States. We also investigate the negative environmental impact of the mining of these rare earth and precious metals. Namely, the use of fossil fuels for mining.

The structure of our paper is as follows. In Section 2, we discuss the materials that are needed to build 5G base stations. In Section 3, we discuss the methods that we use to estimate the amount of each used in each 5G base station. Then in Section 4 we estimate the total number of 5G base stations that need to be deployed to provide nationwide coverage in the U.S. Finally, In Section 5 we discuss the environmental trade-offs of deploying a 5G network.

II. 5G BASE STATION COMPONENTS AND MATERIALS

In this section, we describe the high-level components in 5G base stations and the essential materials used in each component. We compare these components with their counterparts in 4G base stations, and explain why replacing base stations is necessary to provide the reduction in latency and improvement in bandwidth that 5G promises over 4G.

Nearly every component in base stations—including antennas, filters, power amplifiers, and PCBs—must be upgraded to enable 5G networks. Unfortunately, a significant amount of rare and valuable metals need to be mined and manufactured to build these upgraded base station components.

A. Base Station Components

A 5G base station has two main components, the Active Antenna Unit (AAU) and baseband processing unit (BBU). The AAU receives and transmits signals, filters signals, removes noise, and converts signals from the Radio Frequency (RF) domain to and from the optical domain. It consists of an antenna, antenna enclosure, and microwave circuits such as filters and power amplifiers. The AAU circuitry requires a variety of precious and rare earth metals to transmit and receive RF signals at the high frequencies used by 5G. The BBU consists of a server and digital cards fulfilling functions like channel encoding/decoding, baseband signal modulation/demodulation, protocol processing, and functions for networking protocols. The BBU can be divided into Centralized Unit (CU) and Distributed Unit (DU). Usually, one DU is co-located with the AAU at a cell tower and one CU serves multiple DUs. In this work, we only consider the materials used in the DU given that this is the unit deployed in each base station, while the CU is centralized.

Compared to 4G base stations, 5G base stations require upgrading the antennas, amplifiers, filters, and PCBs. The antennas and amplifiers need new materials to handle the higher frequencies and more efficient signal management used in 5G. Also, the PCBs must also be improved to handle 5G's higher bandwidth RF signals and more demanding computation.

5G also requires deploying many base stations to replace one 4G base station. Indeed, one of the ways that 5G will provide an increase in bandwidth is by deploying base stations more densely so there are fewer users per base station. Also, the higher frequency spectrum used in 5G (that also enables more users per base station) cannot travel as far, so base stations need to be deployed closer together—about 250 meters apart. Therefore, every material that is already used in 4G will need to be used more in 5G. For instance, more *Aluminum* will need to be used to make more base station enclosures.

Fig. 1. 5G base station components and materials

B. Technical Improvements from 4G to 5G

We now describe each of the technical improvements of 5G and how these improvements require using new metals and higher quantities of metals in base stations. 5G promises latency under 1 millisecond (ms), while 4G typically ranges from 60-100ms. 4G currently has download speeds limited to only 1 Gbps, but 5G promises to increase this tenfold for maximum download speeds of 10 Gbps [8], [25].

These improvements are primarily due to 5G's use of high-frequency spectrum and massive multi-antenna arrays. 5G uses the 30-300 GHz millimeter-wave (mmWave) RF spectrum [8]. This part of the RF spectrum has a short wavelength and can therefore support higher bandwidth than the longer wavelengths used for 4G. To use mmWave, new antennas and more efficient power amplifiers are required. Another way that 5G achieves its promise of higher bandwidth and increased user capacity is massive Multiple-Input and Multiple-Output (massive MIMO). Massive MIMO can handle up to

22 simultaneous users of the same spectrum by beamforming signals directly to each user, where only one user at a time was supported in 4G [59]. It effectively increases the networks capacity without requiring much additional spectrum resources. Massive MIMO can also increase energy efficiency by targeting signals to each specific user and not wasting energy broadcasting signals to areas where the user is not present. However, massive MIMO requires each base station to have many more antennas than were required for 4G.

Several base station components need to be overhauled with new materials, or increased use of materials, to achieve mmWave and massive MIMO (Figure 1). Both of these technologies require new high quality PCBs—including the antennas, RF boards, and CPU boards—we can not reuse any of these components from 4G. This increase in PCBs with increase the demand for the basic materials used in PCBs including *gold* and *copper*. We next explore the unique materials required for each of the technologies.

C. Materials for mmWave

Millimeter wave communication requires more efficient hardware to receive and transmit the signals. Namely, antennas and filters need to be upgraded to for mmWave. This will require using new metals like gallium, germanium, barium, and yttrium, as well as increased amounts of existing materials used in base stations such as gold and copper.

Antennas: 4G antennas are unable to be used for signals in the mmWave spectrum. mmWave frequency range antennas require the use of new advanced ceramic materials that include a mix of materials like *yttrium oxide* and *barium carbonate*, as well as metals such as *germanium* and *gallium*. These raw materials are collected in an appropriate ratio and then synthesized to provide desirable outputs.

Filters: Advanced filters are also required for mmWave communication. In 4G base stations, acoustic-based filters cover a range of frequencies up to 6 GHz, come in small sizes, and offer an excellent performance-to-cost tradeoff. Unfortunately, analogous filtering options for the mmWave spectrum have major issues in viability, performance, size, availability [35]. Therefore, high magnetization Ni-Zn Ferrite and Li-based spinels are used in 5G filters. However, these filters' metal material usage are fairly small, and commonly found in nature, so we exclude them from our discussion.

D. Materials for massive MIMO

Massive MIMO requires more RF hardware than 4G to support the large number parallel users. Namely, more antennas, amplifiers, and CPUs.

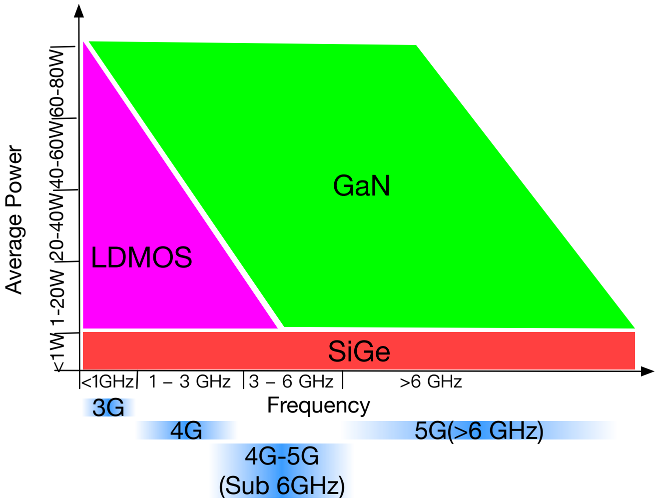
Antennas: Massive MIMO requires large antenna arrays to exploit spatial multiplexing. The antenna matrix in 5G base stations is much denser than the matrix in 4G base stations. 5G base stations will have up to 64 antennas while 4G base stations only have 4 to 8 antennas. This will again require using precious metals in greater quantities than in 4G for antennas in the lower spectrum, and also more rare-earth metals for antennas in the mmWave spectrum.

Power amplifiers: Massive MIMO beamforming techniques demand small, highly-efficient, cost-effective power amplifiers. Since the 5G modulation schemes are more complex compared to 4G networks, its power amplifiers need to be very efficient and linear under a range of frequencies [36]. To achieve this, 5G requires power amplifiers to change from using LDMOS technology to using *gallium nitride (GaN)*. GaN has significantly higher power density, lower parasitics, and improved efficiency at higher frequencies, which is needed to enable multi-band transmit chains. GaN can reduce the size and cost of the radio components [15]. Also, the high-power density of GaN PAs enable small form factors can help reduce the PCB space and therefore overall size of 5G base stations. *Silicon-germanium (SiGe)* can also operate at higher frequencies, however, they only operate at lower power ranges than gallium-based devices. Fig 2 shows the advantage of SiGe is that it can operate at a very wide frequency range, even well into the sub-6 GHz used in both 5G and 4G. In a power amplifier, both GaN and SiGe are used for different purposes: SiGe or Ge is used as the channel on transistors, while GaN or GaAs is used to create semiconductors that can function at high frequencies [10], [25], [26].

In summary, the upgrades made to 5G base stations will require mining metals such as rare-earth metals, precious metals, and other critical metals. In the rest of this paper, we focus on estimating the use of the four rare-earth elements: gallium, germanium, barium and yttrium, one precious metal: gold, and two metals used in all base stations: copper and aluminum.

E. An Overview of the Environmental Impacts

The materials that required to be used in 5G base stations are either rare, found in ores, or highly valuable (or a mixture of all three). This means that mining can only be done in



(*Remake of plot in [46] on page 7*)

Fig. 2. Amplifier materials at different powers and frequencies.

certain locations then shipped to the base station manufacturing facilities, and the metals must be highly processed. The metals often need to be processed until reaching a pure grade of 6 nines in order to ensure they will work as intended. The cumulative process of creating a base station component is highly energy intensive. It is estimated that 76%-80% of global GHG emissions are related to material management in the ICT sector [18], [53].

In addition, there are currently no agreements or policies to determine how to recycle electronic materials, let alone base station materials. We often can not reuse metals from existing base stations because components are often covered in epoxies and other chemicals to prevent weather, chemical, and general damage. There are also no design methodologies consistently used or agreed upon to enable products to be easily reused or refurbished. Legal constraints in mobile networks prevent base station equipment sharing and user device repairing, further increasing material production for private use and lowering collaboration on deployment strategies.

Manufacturing and deploying 5G base stations will be one of the largest technical and global efforts in this decade. We expect the fossil fuels used to manufacture materials to upgrade 5G will contribute to the total fossil fuel consumption in the United States when taking into account mining, manufacturing, transportation, and deployment, and maintenance of the base stations.

III. METHODOLOGY TO QUANTIFY 5G MATERIAL USAGE

We now describe how we estimate the overall environmental impact of 5G base station deployments. To begin, we first calculate the amount of metal materials needed for one 5G base station. We had several issues finding exact figures of material usage in a base station, so we employed a few different methods to estimate material usages. We discuss our estimation accuracy. Next, we used a k-center algorithm combined with real base station deployment data from OpenCellID to estimate the total number of base stations necessary for sufficient 5G coverage across the U.S. Combining these two results allows us to reasonably estimate material usage necessary to deploy 5G base stations across the U.S.

A. *Metal Material requirement for each base station*

In the previous section, we identified several elements that are needed to build 5G base stations, four rare earth elements: gallium, germanium, barium and yttrium, one precious metal: gold, one energy metal: copper, and one lightweight metal: aluminum. Each of these elements will either be used in higher amounts compared to 4G base stations, or used for the first time for 5G base stations. During the course of our research, we found no specific statistics on the quantity of each material used to construct a base station, most likely due vendors not sharing this information because it is considered proprietary information about their business. Therefore, we designed several estimation methods to overcome the lack of information for use of each material. For Gallium, Germanium, Yttrium, Barium and Aluminum we estimate their average use in a base station by dividing the total number of materials used in producing base stations every year by the total number of base stations built each year. For Copper and Gold, we directly estimate the material usage for each of the major components they are used for in base stations.

B. *Estimating Total Amount of Metal Material Usage*

In this section, we show our methods to estimate the total number of 5G base stations required to cover enough customers in the US to compute the amount of each material is required to build the 5G network. In this work, we assume that Wireless ISPs will only use 5G base stations to provide coverage in areas currently covered by their 4G network.

Covering a full area has already been proven to be an NP-hard problem since it can be reduced to set-cover problem. We are, therefore, not able to solve the problem in polynomial time complexity. Moreover, the coverage area of Verizon's 4G network is a non-convex area, so we can not use a convex optimization algorithm to solve it. These problems are exacerbated by the fact that we want to estimate the number of 5G base stations required to cover the whole U.S., this requires significant computational and storage complexity.

Wireless ISPs tend to re-use the mast of base stations they already built. Using data from the OpenCellID data set, we find the geolocation of where users had coverage from existing Verizon 4G base stations. Fig 3 shows Verizon Wireless's 4G base station coverage map from OpenCellID. We can tell that there are some areas not covered by the 4G network at all, and in this work, we assume these areas will continue to lack cellular coverage. Moreover, we assume the coverage range of each 5G base station to be conservatively 450 meters and the coverage of a typical 4G base station to be approximately 10 km.

Given all the assumptions above, to estimate the total number of 5G base stations required to cover the U.S., we use a k-center algorithm to solve this problem. K-center algorithm is a greedy algorithm trying to use minimum number of circles with r radius cover the whole given area, which matches our purpose to cover most areas in the US with least number of base stations. It greedily picks the point in map with maximum

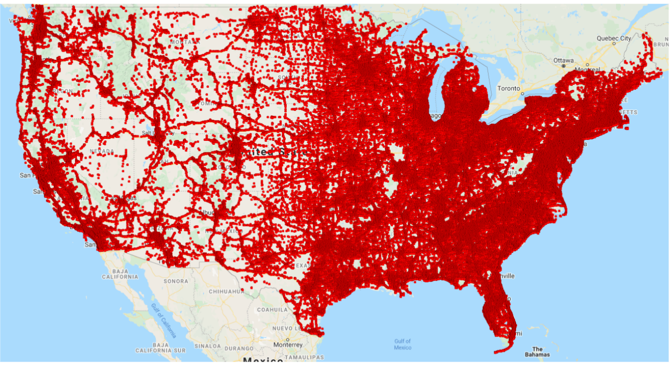


Fig. 3. Verizon Wireless 4G coverage map (59,699,163 data points). Data Source: OpenCellID's crowdsourced cell mapping.

distance to other given centers as a new center until the distance between all centers are less then r. In Alg. 1, we first initialize a U.S. map with longitude and latitude to 3 decimal places and set the distance of each point as INF. Since 0.001 degrees is only about 100 meters, people can arrange the base station within this 100 meter area. Also, considering the computational complexity, this is a suitable degree for us to finish computing in a reasonable time without sacrificing accuracy. Then we put the OpenCellID data into the matrix and update the distance of each point. If the distance is larger than 1 degree from any data point that is covered by an existing base station, we remove that point since. With this matrix, we greedily choose the point with maximum distance in the matrix and put the base station into the matrix and update the distance matrix nearby. The algorithm ends when every point in the matrix has a distance smaller than 0.004.

Algorithm 1: 5G base station deployment estimation algorithm. Calculate the total number of 5G base stations that required to cover the same area as the 4G network.

```
Input: U.S .map with longitude and latitude with three decimal places Output: Base stations deployment map and total number of base stations Data: OpenCellID crowdsourced coverage data.
Function Update $Max_D$:
    for Distance in $M$ do
        if Distance > $Max_D$ then
            $Max_D\_list$ = []
            $Max_D$ = Distance
        ifDistance == $Max_D$
            $Max_D\_list$.append([$Lat_M$,$Lon_M$,$Max_D$]
Function Update M(Point P):
    for Distance in $M$ do
        newDist=$\sqrt{(Lat_M - Lat_P)^2 + (Lon_M - Lon_P)^2}$
        if Distance > newDist then
            Distance = newDist
Initialize an $INF$ Matrix $M$ as the US map.
for $Lat_{OCD}, Lon_{OCD}$ in OpenCellID data do
    Distance = $\sqrt{(Lat_M - Lat_{OCD})^2 + (Lon_M - Lon_{OCD})^2}$
    if Distance >= 0.14 then
        Distance = $INF$
Remove all the $INF$ point in $M$.
$Max_D$ = 0 $Max_D\_list$ = []
Update $Max_D$
while $Max_D$ >= 0.004 do
    for Point in $Max_D\_list$ do
        if Distance == $Max_D$ then
            Update $M$(Point)
            Total++
    $Max_D$ = 0 $Max_D\_list$ = []
    Update $Max_D$
```

IV. RESULTS

In this section, we present our findings of the estimated amount of key materials needed to upgrade cellular base stations from 4G to 5G, as well as their cost in USD. We will also discuss what we believe the environmental impact of this upgrade will be.

Gallium: Gallium (Ga) is rare, hence it is classified as a "rare-earth element". USGS estimates that American manufacturers used roughly 15 tons of gallium in 2020 [60]. About 95% of all gallium produced is used for gallium arsenide (GaAs), which has the ability to convert an electrical current directly into light. Based on [13], [16], we can assume that somewhere around 70% of gallium produced is being used to upgrade wireless networks to 5G, or about 700 tons per year. Given that 138,000 5G base stations were built in 2019 for the U.S. market, we can estimate that about *69 g* of gallium is used per 5G base station. This is a conservative estimation, assuming growth has been around 300%, and the increase in production is attributed to new purposes, specifically enabling 5G capacity [13], [22], [23]. This can be confirmed given that about 97% of global gallium applications are for semiconductor production, yielding that again, around 72% of gallium is used to upgrade the wireless network to 5G [13]. Gallium costs \$0.4 per gram, so it will cost \$27.6 to build a base station [43].

Germanium: Germanium (Ge) is widespread but in low concentrations, and naturally occurs as a sulfide as a companion in copper and zinc ores [12], [19]. From the reasonable source [12], we can conclude that, in the U.S., we are using somewhere around 11 tons of Germanium each year for 5G production. This is again a conservative estimate given that this is just the amount used for fiber optics and not necessarily the amount used to manufacture chips that will be used in 5G base stations and circuitry as well. Given that other end uses, such as infrared systems and polymer catalysts account for about 60% of Ge consumption, we can attribute the remaining 10% to electrical circuitry, which may also end up in 5G base stations [21], [24]. These estimates indicate that, conservatively, about *72 grams* of Ge are needed per base station. This can be further verified by calculating the replacement weight of silicon transistors in chips and estimating their production in the United States. This secondary validation is a much looser estimation, but yields that about 12 tons of germanium is used each year for 5G production [19]. With the number we had, and per gram, germanium costs \$1.45, so it will cost \$104.52 to build a base station [44].

Yttrium: Yttrium(Y) is a silvery-metallic transition metal and is often classified as a rare earth material. It is always found in combination with lanthanides, and is never found as a free element in earth [38]. Yttrium is usually used as yttrium oxide. Yttrium oxide is suitable for making superconductors, as they excel at conducting electricity without any loss of energy. [37] gets data from a Dutch telecommunication service provider about Yttrium usage. It showed that there were 148.75 million of base stations globally with 3.91 tons of yttrium used in 2021. Therefore, we estimate 0.026 g of yttrium will be used in one 5G base station, and yttrium costs $30.5-33.4 per kg, so it will cost $.01 to build a base station since it is used in such small amounts [45].

Barium: Barium (Ba) is one of the alkaline-earth metals which usually used in metallurgy and its compounds are used in a variety of markets including pyrotechnics, petroleum production, and radiology [39]. Barium is used in 5G antennas to improve antenna's key performance indicators, including dielectric constant (Dk), dissipation factor (Df), moisture absorption etc. Barium usually showed up as barium carbonate. [37] also gets data from a Dutch telecommunication service provider with the Barium usage. It showed that 25.82 tons of barium are used for base station in 2021. It shows *0.17g* barium will be used in one 5G base station. And Barium is used in such small quantities that it's cost per base station is neglible, around $0.0002 per base station [45].

Copper: Copper(Cu) is a soft, malleable, and ductile metal with very high thermal and electrical conductivity [40]. Copper is one of the few metals that can occur in nature in a directly usable metallic form, which made it detected very early by humans and it is very popular in lots of markets. Its characteristics of high ductility, and electrical and thermal conductivity, have made it essential for PCBs for base stations. The AAU and BBU both heavily rely on PCBs. We found that copper makes up 40% of the CCL and the CCL makes up 40% of a PCB. Shengyi Technology Co., Ltd's 2020 financial report revealed 73,000 yuan/ton as the estimated price of copper [27]. This allowed us to calculate that 4.08kg of copper is used per PCB. We also found that the AAU and the BBU need PCBs of 0.71 and 0.45 square meters, respectively. One base station usually contains 3 AAU and 1 BBU, so that it needs a PCB of 2.57 square meters. In total, about *10.5 kg* copper is used per base station. To validate our data, we found another sources of copper usage: [31] said the 2020's usage of copper in China is 20 thousand tons, while the total number of cell tower builts in China is 771,000 [32]. Copper costs $0.01 per gram, so estimate the cost as $109.31 per base station [43].

Gold: Gold(Au) is a bright, slightly orange-yellow, dense, soft, malleable, and ductile metal in a pure form [41]. It is one of the least reactive metals, this makes gold an essential component in PCBs. It has incredible electrical conductivity but is too expensive to use as a base for PCBs. Therefore, gold salt is used to electroplate a very thin layer of gold onto the board. Similarly, we can not find the exact proportion of gold per base station directly. We found gold salt is 8% of the cost of total PCB and gold accounts for 68% of the weight in gold salt. We use $1,600/ounce as the estimation price of gold salt and use Shengyi Technology's financial report [27]. We estimate that there is 0.29g of gold per square meter of PCB, so *0.74g* of gold are used per base station. Gold is the most expensive metal used, costing $61.442 per gram, but is used in small amounts, so will only cost about $46.13 per base station [43].

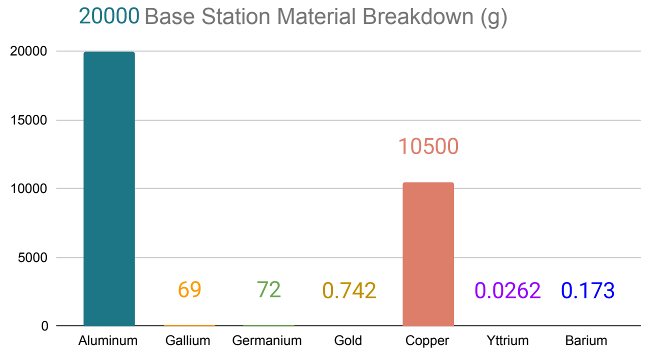


Fig. 4. The Weight Breakdown of Each Material in a 5G Base Station.

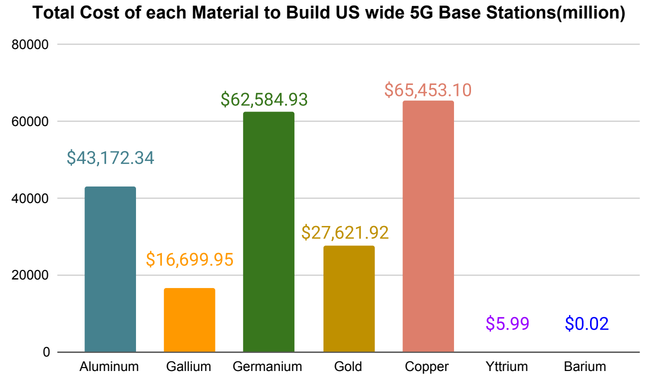


Fig. 5. Total cost of materials used to build enough 5G base stations to cover Verizon Wireless's U.S. network.

Aluminum: [33] estimates that there will be 11 thousand tons of aluminum in China used for 5G base stations during 2020 while the total estimation number of base station they gave were 550,000, which means *20kg* of aluminum will be used per base station. Aluminum (Al) is a very light, soft and extendable metal. It is very common, which is the twelfth most common element in the universe. This makes aluminum very cheap. However, the production process is very high energy consumption. The production of aluminium starts with the extraction of bauxite rock from the ground. The bauxite is processed and transformed using the Bayer process into alumina, which is then processed using the Hall–Héroult process, resulting in the final aluminium metal [42]. Therefore, producing Aluminum is actually not very environmentally friendly. From the former section, we show that Aluminum is mainly used for building up the enclosure of base stations, leading to 20 kg of aluminum used per base station. While aluminum is used in the highest amount per base station, it only costs $0.0034 per gram, so will only amount to $72.10 per base station [43].

We include a material breakdown in weight per base station in Figure 4. Based on the algorithm from Section 3 we found that Verizon Wireless Network would need about 598,784,229 base stations in total to cover the enough area to serve every Verizon Wireless customer currently covered by an existing 4G base station. In Fig 5 we show the total cost of materials that we need to build up 5G base stations for Verizon Wireless to provide coverage across the entire U.S. We can tell that although Gallium and Germanium's usage are not as high as Aluminum and Copper, they are rare and expensive metals. Also we find that we need about 43,172.34 million dollars Aluminum which is approximately one thousand Golden Gate Bridges worth of material. It even requires 27,621.92 million dollars of Gold which is about two days global Gold transaction number.

We note that this ballpark estimate of material and cost for 5G base stations may be on the high end, given that providers may decide they do not want to replace every 4G base station with 5G. Especially since 5G's primary benefits is in providing high-speed wireless replacements for residential wireline connections, and for dense cities. Conservatively, providers will need at least double the amount of 4G base stations currently deployed to achieve the same coverage with 5G. That does not even take into account that 5G may be used to cover new areas untouched by 4G base stations, such as residential and industrial connections, as previously mentioned. We note that one of the primary threats to validity of our results is the difficulty in sourcing accurate figures on the import and use of these metals. To be as accurate as possible we cross-compared several sources and figures, used empirical data on base station construction that has been made public, and we were conservative in any estimate we made.

V. DISCUSSION

In this section, we discuss the sustainability of building and deploying new base stations for every new generation of cellular technology. We also use 5G as a case study to investigate the environmental tradeoffs of replacing base stations that use out-of-date technology with newer and more efficient equipment.

A. Sustainability of Manufacturing Base Stations

Upgrading a cellular network requires manufacturing thousands of base stations out of their constituent materials. Base station materials have three stages in their life cycle: raw material acquisition, production, and end of life. Each material used introduces has its own sustainability concerns at each part of the life cycle. Here, we perform a modified Life Cycle Assessment (LCA) of base stations in the United States based on our literature review. LCAs of base stations do not currently exist due to the massive scope, difficulty of sourcing public information on material usage, lack of recycling and clandestine nature of hardware recycling in general, and possibly also lack of public interest.

a) Acquisition: Base stations are primarily constructed of aluminum and steel. Indeed, these metals account for about 50-90% of the materials used in all telecommunication products [18]. Copper, gold, and other valuable metals also needed, as well as Germanium, gallium, and other rare earth metals used in low quantities in semiconductor chips. Each of these metals must be mined, usually in the form of ores, then processed to produce the pure element that can then be used to manufacture the base station parts. The mining process alone consumes a significant amount of fossil fuels to run the machinery to actually mine the metal [47], [49]. Another important impact to consider is that mining the raw materials contributes to ecotoxicity, polluting ecosystems and introducing toxins to humans [50]–[52]. In addition, both the minerals, raw materials, and fossil fuels used to build the ICT are finite resources. It is estimated we have already used about 50% of available copper [49]. In the near future it is likely that it will become economically infeasible to continue to mine low-grade ores and instead better to extract material from scrapped components. Given that this process already uses fossil fuels to an extent that is deemed economically and environmentally infeasible now, consider the future state of raw material acquisition. As we upgrade from 4G to 5G, we will not be reusing any existing materials, increasing ecotoxicity, and downgrading quality of available materials.

b) Production: After acquiring the raw material, the ores are processed to refine the metals and then manufacture them into usable formats for the base station [48]. To fabricate the semiconductor wafers, many toxic chemicals are used. For every one kilogram input of silicon, there is 280 kg of processing chemicals used [4]. It has also been estimated that 3.6 million liters of water are used per kg of silicon for wafer processing [4], [48]. All of these chemicals need to be purified, and rigorous purification is particularly energy-intensive – distillation alone accounts for 7% of the energy consumption of the U.S. chemical industry [4]. Reaching just 99% pure grades requires several mJ/kg [4]. For instance, using a conversion factor of 320g of fossil fuels burned to generate one kWh, it can be estimated that 1200 g of fossil fuels are needed to produce a 2-gram DRAM chip [48]. Also, many materials are wasted during processing. For instance, 1 cm^2 of input silicon corresponds to .16g of silicon wafer output [4]. This ratio worsens for materials such as germanium that are just used in the semiconductor channels.

c) End-of-life: While 92% of the materials in a base station can be recycled, nearly none are [18]. At best, about 30% of materials are either recycled or reused [50], [53], [54]. Aluminum is often combined with magnesium to form an alloy, making it economically infeasible to recycle it. Smaller products also are economically infeasible to recycle. In addition, the circuitry is often coated with epoxy to protect it from damage, meaning a chemical would have to carefully strip away epoxy to even reach the metals underneath. Therefore, the rare-earth metals, precious metals, and energy metals are used once and thrown away. E-waste (such as circuit boards) are often thrown in a landfill or burned [47], [48]. E-waste is the fastest growing streams of waste globally and growing three times faster than other waste streams [50], [53]. In addition, 80% of the CO2 emissions produced by the ICT sector come from "raw material acquisition, production, End of Life Treatment (EoLT), and transports"; therefore, recycling materials will not benefit the environment as much as reuse and reduction measures [49].

B. Environmental Benefits of 5G Base Stations

Despite the negative environmental impacts from manufacturing, deploying 5G base stations will undeniably have many positive impacts on the environment as well.

1) Improving Energy Efficiency of Cellular Networks: New 5G base stations are essential to increase the capacity and energy efficiency of the network, existing 4G technology simply cannot provide the same benefits. 5G requires more power to operate at higher frequencies, but 5G technology aims to introduce energy efficient designs, including centralizing processing using cloud computing and separate BBU and AAU units. These changes will make it possible to have less processing occur in the field where it is least efficient because there are fewer opportunities for sharing underutilized hardware. 5G will also enable faster, lower latency, communication so that communication can complete in shorter time periods. Both of these will result in base station infrastructure only being used when it needs to be used, saving energy compared to 4G technology that is constantly running and takes longer to process traffic [58].

Due to its improved computing and power usage, the 5G network has the potential to help reduce greenhouse gas emissions. Indeed, international standards have called for 5G to use much less energy to run then 4G [28]. They estimate that in 4G 1 kWh of electricity is used to download 300 high-definition movies; while in 5G, one can download 500 ultra-high-definition movies using the same amount of energy.

2) Improving efficiency of other infrastructure: Using the 5G network will provide some benefits that could counter the initial costs [6]. As reported in [30], one company developing machinery for the advanced-industries sector was able to achieve material savings in excess of 10% across its product line by implementing 5G monitoring devices. Also, more and more manufacturing industries have already started considering implementing 5G into their supply chains. It is estimated that more than half of manufacturers (56%) report they will be testing or using 5G in some capacity within their facilities by the end of 2021 [29]. Over 98% manufacturers believe they will implement 5G network into their facility at some point.

C. Mitigating environmental impacts of 5G deployments

Even though introducing 5G base stations cause GHG emissions, 42.8% of significant reduction can be achieved by optimizing power structure and base station layout strategy [56]. Therefore, according to our paper, we can tell if three major wireless providers in the US can cooperate with each other to optimize 5G base station implementation, the GHG emission can be reduced significantly. Moreover, the raw materials acquisition and the scrapped components are the part of the process that are unsustainable and unnecessary. To decrease 5G demand and reuse 4G legacy base stations, there are proposals of deploying 5G internally in large industry settings and using 4G base stations for external connections and compute. This reuse of components and existing infrastructure could result in reductions in predicted metal depletion by 35%, climate change by 16%, and human toxicity by 26% [54], [55].

Also, a Huawei white paper about environmental benefits of the 5G network mentioned that together with virtualisation, edge computing, AI-enabled analytics and cloud, 5G can help industries implement a new process of energy efficiency programs by supporting the most efficient and flexible allocation of resources [6]. It can help reduce energy consumption in many ways including: smart energy management device support, reduce office place and business travel, efficient just-in-time supply chains enabled by predictive analytics, and intelligent vehicles carrying people and goods. Research and modelling indicate that 5G lifecycle assessment (LCA) and operation parameter comparison can further reduce energy consumption. Impressive examples were listed, such as: 5G consultations saved 4 medical experts from needing to take regular flights to regional hospitals while the quality of consultations remained unchanged. The elimination of road and air travel reduced 99% GHG emissions associated with these expert consultation sessions. Also, a leading smartphone manufacturer in Guangdong, China replaced manual quality assurance checks, allowing assembly lines with a system of 5G network AI cameras connected to an edge server to increase the speed of inspection by almost 18 times and reduce each smartphone energy consumption by 6%.

VI. CONCLUSION

In this paper, we examine the difference between 4G/LTE and 5G base stations and the materials that facilitate this upgrade. 5G performance improvements are enabled through mmWave and massive MIMO as well as smaller coverage areas. We found that overhauling base station infrastructure to add this new technology requires new materials, higher quality materials, and overall a significantly increased use of materials. Unfortunately, we found most of these materials are rare-earth or precious metals. We found 5G relies on gallium and germanium, which are expensive and difficult to mine, and copper which is a severely constrained resource. Beyond the materials themselves, deploying these new base stations will have a significant environmental toll from sourcing, transporting, manufacturing, and installation. GHGs are released at every step, recycling is largely infeasible, and the metals are available in small quantities, making the roll out of a this new generation of wireless infrastructure environmentally taxing.

However, we also found 5G has the potential to reduce energy consumption compared to 4G because it has better power management, and higher performance. This may result in less energy used for communication in the future, reducing the net greenhouse gas emissions that would otherwise by incurred by continuing to use inefficient 4G networks. Additionally, to mitigate the environmental cost of raw material acquisition and processing, we should consider using 5G in conjunction with existing 4G infrastructure, and maintaining that 4G infrastructure for the long term.

VII. ACKNOWLEDGEMENTS

This work was partially supported by NSF award #2213689.

REFERENCES

[1] 5G NR Transmission Time Interval: 2021. Accessed: 2021- 10- 07.

[2] Albert Manfredi. 2018. How 5G Wireless Network can be Deployed with Existing 4G Infrastrucure?. (May 2018). Retrieved October 7, 2021 from https://www.researchgate.net/post/How-5G-Wireless-Network-can-be-Deployed-with-Existing-4G-Infrastrucure

[3] Claire Hurran. 2020. University of Washington: What Will 5G Mean for the Environment?. International Policy Institute Report. University of Washington, Seattle, WA.

[4] Eric D. Williams, Robert U. Ayres, and Miriam Heller. 2002. The 1.7 Kilogram Microchip: Energy and Material Use in the Production of Semiconductor Devices.Environmental Science & Technology 36, 24 (2002), 5504-5510.DOI: 10.1021/es025643o

[5] Frenger, P. and Tano, R. 2021. More capacity and less power: How 5G NR can reduce network energy consumption. IEEE 89th Vehicular Technology Conference (2021).

[6] Huawei Technologies CO., Ltd. 2020. GREEN 5G: Building a sustainable world

[7] iPCB. 2019. 4G and 5G base station structure and 5G PCB usage. (June 2019). Retrieved October 7, 2021 from https://www.ipcb.com/news/118.html

[8] Learn the key differences between 4G vs. 5G networks: 2020. https://www.techtarget.com/searchnetworking/feature/A-deep-dive-into-the-differences-between-4G-and-5G-networks. Accessed: 2021- 10- 06.

[9] Marc A. Angulo. 2018. Mineral Resource of the Month: Cesium. U.S. Geological Survey. American Geosciences Institute.

[10] Materials Used in 5G Communication – Scitech Patent Art: 2021. https://www.patent-art.com/knowledge-center/materials-used-in-5g-communication/. Accessed: 2021- 10- 06.

[11] O'Connell, E. et al. 2020. Challenges Associated with Implementing 5G in Manufacturing. Telecom. 1, 1 (Jun. 2020), 48–67.

[12] Peide D. Ye. 2016. Switching Channels. In Proceedings of IEEE Spectrum, December 2016. IEEE. https://spectrum.ieee.org/germanium-can-take-transistors-where-silicon-cant

[13] Pouya Yarahmadi Dehnavi. 2013. Global Cycle of Gallium Production, Use and Potential Recycling. Master's thesis. Royal Institute of Technology (KTH), Stockholm, Sweden.

[14] Radio Frequency Systems. 2016. An RFS Guide to Common Public Radio Interface Panels. Radio Frequency Systems.

[15] Rick Mills. 2020. 5G and Metals. (June 2020). Retrieved October 6, 2021 from https://www.sharecafe.com.au/2020/06/24/5g-and-metals/

[16] Roger Franz. 2016. How Will We Get the Gallium?. Electronic Media. Endeavor Business Media.

[17] Sebastian Anthony. 2013. A rare look inside an LTE cell site, operated by Sprint in San Francisco. (June 2013). Retrieved October 7, 2021 from https://www.extremetech.com/extreme/158342-a-rare-look-inside-an-lte-cell-site-operated-by-sprint-in-san-francisco

[18] Tanskanen, P., Kallio, S. and Scheck, H. 2018. CIRCULAR ECONOMY IN TELECOMMUNICATIONS-CLOSING THE LOOP. CARE Innovation (Vienna, 2018).

[19] The Editors of Encyclopaedia Britannica. 2021. germanium. (March 2021). Retrieved October 18, 2021 from https://www.britannica.com/science/germanium

[20] Unwired Labs, https://www.opencellid.org/

[21] U.S. Department of the Interior. 2005. GERMANIUM END-USE STATISTICS. U.S. Geological Survey, Data Series 140. USGS.

[22] U.S. Department of the Interior. 2017. Critical Mineral Resources of the United States—Economic and Environmental Geology and Prospects for Future Supply: Gallium. U.S. Geological Survey.

[23] U.S. Department of the Interior. 2020. GALLIUM. U.S. Geological Survey, Mineral Commodity Summaries. USGS.

[24] U.S. Department of the Interior. 2020. GERMANIUM. U.S. Geological Survey, Mineral Commodity Summaries. USGS.

[25] Westberg, E., Staudinger, J., Annes, J. and Shilimkar, V. 2021. 5G Infrastructure RF Solutions. IEEE Microwave Magazine.

[26] White, A. 2019. ELECTRONIC METALS DEMAND Spotlight on 5G technologies. Argus Media.

[27] Shengyi Technology Co. Ltd, 2020, http://download.hexun.com/ftp/all_stockdata_2009/all/120/947/1209477921.pdf

[28] Renee Cho, 2020, https://news.climate.columbia.edu/2020/08/13/coming-5g-revolution-will-affect-environment/

[29] TheManufacturingInstitute.org, 2021, https://www.themanufacturinginstitute.org/wp-content/uploads/2021/03/Manufacturing-Institute-5G-study.pdf

[30] Paolo Benedet, Ivo Nikolov, 2022, Winning the war for talent in product development.

[31] Pokertrader,2019 https://posts.careerengine.us/p/5f029e14c523b112e058d9dc

[32] Juan Pedro Tomás, 2021, https://www.rcrwireless.com/20210519/business/china-ends-q1-819000-5g-base-stations-report

[33] Yu Zhang, 2020, https://www.mymetal.net/20/0326/16/4E3E9864D3F494B3.html

[34] 5G Mobile Networks: A Systems Approach, 2020, https://5g.systemsapproach.org/ran.html

[35] Approaching The 5G MmWave Filter Challenge, doEEEt Media Group, 2020, https://www.doeeet.com/content/eee-components/rf-mw/approaching-the-5g-mmwave-filter-challenge/

[36] David Schnaufer, Bror Peterson, 2018, Realizing 5G Sub-6-GHz Massive MIMO Using GaN,https://www.mwrf.com/technologies/semiconductors/article/21849362/realizing-5g-sub6ghz-massive-mimo-using-gan

[37] Flik, Gloria. "Material Criticality for Future Telecommunication Technologies: Scenario Development and Supply Chain Resilience Strategies." (2021).

[38] Wikipedia, https://en.wikipedia.org/wiki/Yttrium#: :text=Yttrium is a chemical element,%22rare%2Dearth%20element%22., 2022

[39] Wikipedia, https://en.wikipedia.org/wiki/Barium, 2022

[40] Wikipedia, https://en.wikipedia.org/wiki/Copper#Electronics_and_related_devices, 2022

[41] Wikipedia, https://en.wikipedia.org/wiki/Gold, 2022

[42] Wikipedia, https://en.wikipedia.org/wiki/Aluminium, 2022

[43] Daily Metal Prices, 2022, https://www.dailymetalprice.com/metalprices.php?c=al&u=oz&d=1

[44] Germanium. Trading Economics. 2022. https://tradingeconomics.com/commodity/germanium

[45] Current prices of rare earths. ISE. 2022. https://en.institut-seltene-erden.de/aktuelle-preise-von-seltenen-erden/

[46] Eric Westberg, 2019, NXP RF Solutions Enabling the 5G Revolution.

[47] Benjamin W. Cramer. 2012. Man's need or man's greed: The human rights ramifications of green ICTs. Telemat. Inf. 29, 4 (November, 2012), 337–347. https://doi.org/10.1016/j.tele.2011.11.003

[48] Bardi, Ugo. (2014). Extracted: How the Quest for Mineral Wealth Is Plundering the Planet.

[49] Guldbrandsson, F. & Bergmark, Pernilla. (2012). Opportunities and limitations of using life cycle assessment methodology in the ICT sector. Electronics Goes Green 2012+, ECG 2012 - Joint International Conference and Exhibition, Proceedings. 1-6.

[50] Boluda, Inès & Patitsas, Elizabeth & McMahan, Peter. (2021). What do Computer Scientists Know About Conflict Minerals?. LIMITS Workshop on Computing within Limits. 10.21428/bf6fb269.64063bd7.

[51] Pargman, Daniel & Wallsten, Björn. (2017). Resource Scarcity and Socially Just Internet Access over Time and Space. 29-36. 10.1145/3080556.3084083.

[52] Persson, Linn & Carney Almroth, Bethanie & Collins, Christopher & Cornell, Sarah & de Wit, Cynthia & Diamond, Miriam & Fantke, Peter & Hassellöv, Martin & MacLeod, Matthew & Ryberg, Morten & Jørgensen, Peter & Villarrubia-Gómez, Patricia & Wang, Zhanyun & Hauschild, Michael. (2022). Outside the Safe Operating Space of the Planetary Boundary for Novel Entities. Environmental Science & Technology. XXXX. 10.1021/acs.est.1c04158.

[53] Franquesa, David & Navarro, Leandro & Lopez, David & Bustamante, Xavier & Lamora, Santiago. (2015). Breaking Barriers on Reuse of Digital Devices Ensuring Final Recycling. 10.2991/ict4s-env-15.2015.32.

[54] Franquesa, David & Navarro, Leandro. (2018). Devices as a commons: limits to premature recycling. 1-10. 10.1145/3232617.3232624.

[55] Franquesa, David & Navarro, Leandro & Bustamante, Xavier. (2016). A Circular Commons for Digital Devices Tools and Services in eReuse.org. 10.1145/2926676.2926684.

[56] Ding, Yangxue & Duan, Huabo & Xie, Minghui & Mao, Ruichang & Wang, Jiajia & Zhang, Wenbo. (2022). Carbon emissions and mitigation potentials of 5G base station in China. Resources, Conservation and Recycling. 182. 106339. 10.1016/j.resconrec.2022.106339.

[57] ALYSSA DANIGELIS, SEPTEMBER 25, 2017, NYC's Empire State Building Takes Energy-Efficiency To New Heights.

[58] Pihkola, Hanna, et al. "Energy consumption of mobile data transfer-Increasing or decreasing? Evaluating the impact of technology development & user behavior." ICT4S. 2018.

[59] P. Harris et al., "Serving 22 Users in Real-Time with a 128-Antenna Massive MIMO Testbed," 2016 IEEE International Workshop on Signal Processing Systems (SiPS), Dallas, TX, USA, 2016, pp. 266-272, doi: 10.1109/SiPS.2016.54.

[60] Shane Lasley, "Techy gallium overshadowed by rare earths", September 9, 2021, https://www.metaltechnews.com/story/2021/09/09/critical-minerals-alliances/techy-gallium-overshadowed-by-rare-earths/695.html