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The energy use implications of 5G: Reviewing whole network operational energy, embodied energy, and indirect effects

Abstract

The energy efficiency and consumption of mobile networks has received increasing attention from academics and industry in recent years. This has been provoked by rapid increases in mobile data traffic and projected further rapid increases over the next decade. As a result, dramatic improvements in the energy efficiency of mobile networks are required to ensure that future traffic levels are both environmentally and economically sustainable. In this context, a good deal of research has focused on technologies and strategies that can improve the energy efficiency of 5G and future mobile networks more broadly. However, existing reviews in the field of green or sustainable mobile communications on the topic of the energy use implications of 5G overlook a number of issues that broader literatures on the energy use impacts of ICTs suggest could be significant. Addressing this gap, we conduct a literature review to examine whole network level assessments of the operational energy use implications of 5G, the embodied energy use associated with 5G, and indirect effects associated with 5G-driven changes in user behaviour and patterns of consumption and production in other sectors of the economy. In general, we find that these issues and their energy use implications have received insufficient attention in publicly available studies on the energy use impacts of 5G.

Keywords

5G, mobile networks, green mobile networks, narrative review, energy efficiency, energy consumption, energy demand, sustainability, embodied energy, rebound effects, user behaviour, indirect effects

Abbreviations

2nd generation mobile network (2G)

3rd generation mobile network (3G)

4th generation mobile network (4G)

5th generation mobile network (5G)

Artificial intelligence (AI)

Base station (BS)

Bits per second per Hertz (b/s/Htz)

Carbon dioxide (CO2)

Carbon dioxide equivalent (CO2e)

Compound annual growth rate (CAGR)

Computed tomography (CT)

Device-to-device (D2D)

Discontinuous transmission (DTX)

Energy Aware Radio and Network Technologies (EARTH)

European Union (EU)
Exabyte (EB)
Gigabyte (GB)
Gigajoule (GJ)
Gigatonne (Gt)
Gigwatt hour (GWh)
Global e-Sustainability Initiative (GeSI)
Global warming potential (GWP)
Greenhouse gas (GHG)
Groupe Spécial Mobile Association (GSMA)
Heterogeneous network (HetNet)
Information and communication technology (ICT)
Instant messaging (IM)
Institute of Electrical and Electronics Engineers (IEEE)
Intergovernmental Panel on Climate Change (IPCC)
Internet of Things (IoT)
Joule per bit (J/bit)
Kilogram (kg)
Kilometre (km)
Kilowatt per kilometre squared (kW/km2)
Kilowatt hour (kWh)
Lifecycle assessment (LCA)
Long-term evolution (LTE)
Massive multiple-input multiple-output (M-MIMO)
Megabyte (MB)
Megabytes per second per kilometre squared (MBps/km2)
Mega tonne (Mt)
Millimetre wave (mmWave)
Multimedia messaging service (MMS)
Network function virtualisation (NFV)
Next Generation Mobile Network Alliance (NGMN)

Non-government organisation (NGO)

Personal computer (PC)

Quality of Service (QoS)

Radio access network (RAN)

Short messaging service (SMS)

Television (TV)

Terawatt hour (TWh)

Tonne (t)

United Kingdom (UK)

Visible light communication (VLC)

World wildlife fund for nature (WWF)

Word count: 16,374

1. Introduction

The last decade has seen increasing attention paid to the energy used by information and communication technologies (ICTs) by academia, industry and the media. Industry scenarios tend to emphasise the energy saving potential of increasing adoption of ICTs, due to improvements in energy efficiency and structural changes as virtual processes replace physical processes [1]. However, adoption of ICTs may also drive increasing energy consumption, due to direct effects from production, use and disposal of ICTs and indirect and rebound effects driving higher levels of consumption of services and wider economic growth [2]. In this paper, we review the evidence on these drivers of decreasing or increasing overall energy use at the network level for the next generation of mobile communications technologies currently being introduced, known as 5G.

A range of contrasting estimates has been produced for the contemporary and future energy use and carbon footprint of global ICT. For instance, Malmodin and Lunden estimated that the carbon footprint of global ICT in 2015 was 730Mt CO2e (1.4% of the global footprint), whilst its operational energy consumption was 805 TWh (3.6% of global electricity use) [3]. These findings were a small increase from estimates for 2010 [4], but represented a steady decline in carbon footprint and electricity consumption per subscriber and per GB. Having previously estimated that ICTs carbon footprint would reach 1100 MtCO2e by 2020 (1.9% of global emissions) [4], Malmodin and Lunden forecast that the carbon footprint of ICT would fall slightly between 2015-2020 [3].

The Global e-Sustainability Initiative (GeSI) have produced slightly higher estimates. In 2012, they estimated that global ICTs carbon footprint was 0.9 GtCO2e in 2011 (1.9% of global emissions) and forecasted that its 2020 carbon footprint would be 1.27 GtCO2e (2.3% of global emissions) [5]. A later report, estimated that ICTs 2030 carbon footprint would fall to 1.25 GtCO2e (1.97% of global emissions) [1]. Finally, Andrae and Edler estimate an even higher electricity use and carbon footprint of global ICT. Their mid-case scenario estimated that in 2010 global ICT consumed 2,037 TWh (11% of global electricity use) and emitted 1.3 GtCO2e, and forecasted that this would rise to 2,878 TWh (11% of global electricity use) and 1.7 GtCO2e in 2020, and again to 8,265 TWh (21% of global electricity use) and 4.8 GtCO2e by 2030 [6,7]. A critical review of these attempts to estimate the carbon footprint of ICT is offered by Freitag et al. [8].

Within this area of interest, telecommunications and in particular mobile communications have received attention. Estimates of rapid growth in mobile data traffic have in particular spurred efforts across academia and industry to identify technologies and strategies that can dramatically improve the energy efficiency of mobile networks. For instance, Ericsson estimate that global mobile data traffic hit 51 EB/month in 2020 and is forecasted to grow to 226 EB/month by 2026 at a compound annual growth rate (CAGR) of 28% [9]. Energy efficiency improvements have therefore come to be seen as essential in order for mobile networks to serve future mobile traffic demands in an environmentally and economically sustainable fashion. For instance, the Next Generation Mobile Network Alliance (NGMN) industry body has suggested that 5G will be required to improve network energy efficiency by x2,000 [10]. These twin environmental and economic rationales have driven the emergence of a burgeoning literature on energy efficient, green or sustainable mobile communications.

As the first generation of mobile network to emerge within this context, energy efficiency has been an important consideration through-out the development, standardisation and implementation of 5G. In simple terms, mobile networks wirelessly connect portable user devices to wider communications networks and the internet to enable the transmission of voice and data. Radio access networks (RANs) comprised of base stations (BSs) connect user devices to the network wirelessly by exchanging information using radio waves. Transmission networks then link RANs to the core networks that connect users to other users or the internet. The fifth and latest generation of mobile communication, 5G is in the relatively early stages of its roll-out across the world. Using higher bands of the radio wave spectrum than have previously been used for mobile communications, 5G offers a range of benefits such as high download speeds, low latency and high connections densities. These capabilities are expected to be exploited in a range of applications across three families of use cases: enhanced mobile broadband (e.g. virtual reality), ultra-reliable and low latency communications (e.g. autonomous vehicles) and massive machine type communication (e.g. ‘Internet of Things’ applications) [11].

The energy use of future mobile networks, and whether approaches to improve their energy efficiency will lead to reductions in overall energy consumption, are therefore highly significant research areas for academia and industry alike. As we will detail below however, current reviews on the topic have a narrow focus on reducing the operational energy use of RANs and are overwhelmingly populated by studies focusing on single technologies in isolation. These reviews therefore give the impression of a research field that is lacking in whole network assessments, and paying insufficient attention to potentially significant embodied energy use and indirect energy effects. The purpose and contribution of this review therefore is to intentionally investigate and establish whether these are blindspots of the existing reviews or of current knowledge about the energy use implications of 5G in general; and, in the case of the latter, to use studies about these effects in the broader context of ICTs to clarify their potential importance in relation to 5G.

In the following section we explore a number of existing reviews on the energy use implications of 5G and future mobile networks more broadly. We highlight and briefly explain the range of technological solutions that they cover but also identify three potentially significant gaps in present understanding about the energy use implications 5G. These are the overall operational energy impacts seen from a whole network perspective, the impact of the embodied energy associated with network infrastructure and user devices, and indirect effects associated with 5G-driven changes in user behaviour and patterns of consumption and production in other sectors of the economy. In section three we elaborate and justify the narrative review approach taken in this study. Our findings are then presented in section 4. We initially consider direct energy effects in sections 4.1.1 (whole networks assessments) and 4.1.2 (embodied energy and lifecycle assessments), followed by indirect energy effects in sections 4.2.1 (rebound effects) and 4.2.2 (enablement effects). Finally, in our discussion and conclusions section, we summarise our findings and discuss the implications of our work, including suggestions for further research.

2. Existing reviews on 5G and green mobile networks

A number of reviews have already been conducted into the energy saving potential of technologies and strategies associated with 5G and green mobile networks more broadly. It is worth making a distinction between efforts to reduce the energy demands of mobile networks and increase the use of renewable energy within mobile networks on the one hand, and the role 5G could play in saving energy by enabling so-called 'vertical industries' such as smart grids and autonomous automotive systems on the other. In this section the focus in on the former two categories, whilst the latter is dealt with in our consideration of the 'enablement effect' in section 4.2.2 below. The technologies highlighted by these existing reviews are summarised in Table 1.

Table 1: Green 5G enabling technologies (adapted from Buzzi et al. 2016 and Zhang et al. 2019)

Technology	Description
Network deployment and dynamic adaptation	
Sleeping strategies	Switching off network components in low traffic conditions. May involve sleeping particular components within BSs (e.g. power amplifiers or cooling equipment) or switching off some BSs entirely. Sleeping can also occur at various depths and over various time periods. For example, an approach referred to as discontinuous transmission (DTX) powers-down BS components during idle periods in the millisecond range.
Cell zooming	Cell zooming involves BSs dynamically adjusting their coverage area and so transmit power based on the location and Quality of Service (QoS) requirements of users. Cell zooming is often proposed in combination with sleeping strategies in order to fill coverage holes caused by switching off a BS, or to balance traffic across the network in order to maximise scope for BS sleeping.
Dense HetNets	Dense Heterogeneous Networks (HetNets) involve different sizes of BS serving the same geographical area (usually urban hotspots), most typically a layer macro BSs with a number smaller BSs (e.g. micro BSs) within their cells. In combination with sleeping strategies, they save energy by serving traffic hotspots more efficiently through lower power micro-BSs and shorter transmission distances. They also enable the decoupling of control and data functions, expanding the scope for BS sleeping (see 4.1.1 below).
Transmission techniques and traffic offloading	
D2D	Device-to-device (D2D) communication involves utilising the position of user devices in order to limit transmission distances. Most obviously, this involves two devices in close proximity communicating directly with one another (direct one-hop D2D), without needing to link via the BS. Multi-hop D2D communication involves user devices helping other user devices to communicate with each other or a BS. As such, with D2D communication, user devices are not just served by the network, but become productive nodes within it.
Relays	Working on the same principle as multi-hop D2D, relaying involves using dedicated relay stations to reduce transmission distances between BSs and user devices and so save energy.
M-MIMO	Massive multiple-input multiple-output (M-MIMO) refers to large arrays (potentially hundreds) of antennas at BSs, allowing multiple users to be served simultaneously. This improves energy efficiency by enabling large multiplexing and array gains (see Prasad, Hossain, and Bhargava 2017).
Radio resource management	Optimising the allocation of radio resources (e.g. bandwidth, time) in order to maximise energy efficiency or minimise energy consumption.
Traffic offloading	Balancing traffic load across various available radio access technologies (e.g. cellular, WiFi) in order to maximise energy efficiency.
VLC	Visible light communication (VLC) is a highly energy efficient communications technique that uses the visible light spectrum to transmit information. Suitable for indoor contexts, indoor traffic could be offloaded to VLC, which would free up 5G capacity and save energy.
New architecture paradigms	
Cyberforaging	Offloading computationally complex tasks to nearby servers, so reducing user device energy consumption.
Local caching	Storing popular content close to the network edge (e.g. at the BS) and so avoiding duplicate transmissions of the same content across the entire

	network and their associated energy consumption.
Mobile edge computing	Mobile edge computing involves hosting applications and services closer to the network edge, reducing energy consumption by shortening the traffic delivery path.
Core network assisted scheduling	Identifying and exploiting delay-insensitive traffic in order to aggregate small data traffic bursts into larger traffic bursts. These larger bursts are more energy efficient due to lower signalling and radio resource scheduling overheads.
Cloud-RAN	Transferring digital signal processing functions from BSs to data centres. Centralising these tasks leads to more efficient cooling.
NFV	Network function virtualisation (NFV) employs cloud computing and virtualisation technologies to decouple network functions from particular hardware types. NFV improves energy efficiency by reducing the need for custom hardware and improving resource utilisation.
Green energy harvesting and transfer	
Environmental energy harvesting	Harvesting and storing renewable energy in order to power RANs. This could potentially include energy sharing between BSs via wired connections.
Radiofrequency energy harvesting	Harvesting radio frequency energy from radio signals over the air. Again, this could potentially include network nodes sharing energy via wireless power transfer. Seen as being most applicable to IoT devices.
Smart grid enabled green networks	Integrating mobile networks with smart grids. Energy harvesting BSs can act as prosumers, trading energy with the smart grid. BSs and network operators cooperate on energy purchasing, storing, sharing and trading in order to optimise network energy efficiency or maximise renewable energy use.

Piovesan et al. highlight two main network energy efficiency techniques (sleep strategies and cell zooming) and two approaches to reducing the energy use of user devices (D2D communication and cyberforaging), explore wireless power transfer, and review work on energy cooperation (5G networks that harvest and store their own renewable energy) and energy trading (5G networks trading energy with the smart grid) [13]. Zhang et al. explore a wider range of technologies under the headings *energy efficient resource management* (energy efficiency and spectral efficiency trade-off, sleeping and cell zooming, D2D communications, M-MIMO, mmWave technology, dense HetNets), *new architecture and deployment paradigm* (traffic offloading, mobile caching and edge computing, core network assisted scheduling, cloud-radio access networks and network function virtualisation) and *green energy exploration* (environmental energy harvesting, radio frequency energy harvesting, smart grid enabled green networks) (see Figure 1). [14]. Buzzi et al. also cover similar ground, but introduce the consideration of visible light communications as an offloading technique, as well as a range of hardware solutions (e.g. energy efficient power amplifiers and hybrid analog/digital beamformers) [15]. Suarez et al. provide an overview of research approaches in green wireless networks at the component (e.g. power amplifiers), radio resource management (energy efficient radio techniques and transmissions mechanisms, including intelligent ‘cognitive radio’ approaches) and cell layout adaption levels (BS sleeping and cell zooming, HetNet deployments and relays) [16]. Finally, Lorincz et al.’s review of approaches to improving the energy efficiency of radio access networks considers a fairly familiar list of seven approaches, of which only the coexistence of different communication systems in unlicensed spectrum is additional to the approaches already mentioned here [17].

Figure 1: An overview of “green” 5G enabling technologies

Source: [14]

This body of reviews, in general and taken as a whole, has identified a fairly consistent set of technologies that hold promise for improving the energy efficiency of mobile networks. They appear geared toward identifying promising technologies, explaining some of the technicalities about how they work and describing how newer work has addressed the issues identified by older work. Whilst there is also a focus on reporting the findings of the studies surveyed, with the exception of Suarez et al. these reviews tend not to attempt to clearly quantify the kinds of efficiency improvements that certain technologies could achieve. Furthermore, how the surveyed technologies might contribute amongst other approaches at a whole network level is largely overlooked due to a lack of ‘holistic’, whole network perspective studies. As Buzzi et al. themselves point out:

> “In our opinion, the main issue concerning the current state-of-the art is that most research has been directed towards a separate analysis and use of the different energy-efficient technologies… A holistic approach is thus necessary, in which all energy-efficient techniques are combined [15].

As such, the above reviews overwhelmingly highlight studies that assess the potential of single technologies to reduce the operational energy use of radio access networks and user devices through relatively small-scale and simplistic modelling exercises. What is missing therefore from the above body of literature is any explicit attempt to try and identify studies that focus on other crucial issues relating to the energy use implications of 5G and future mobile networks – the energy saving potential of a range of technological interventions at the whole network-level, the embodied energy use of mobile networks, and the indirect energy use impacts of future mobile networks including changes in user behaviour (and strategies to intentionally shape user behaviour). The purpose and contribution of this paper is therefore to intentionally search for studies that do consider these issues, and, if no such studies are found, to highlight the potential significance of such issues for the energy use impacts of 5G.

3. Material and methods: a literature review

After initial scoping literature searches on the topic of the energy use implications of 5G, we decided that a systematic review approach was not suitable at this time. The reason for this was that whist it is growing rapidly, the literature on the energy use implications of 5G is still emerging and so there is a relative lack of high quality, whole network studies with clear quantitative findings. Furthermore, the evidence base is extremely diverse and therefore ill-suited to systematic comparison and tabular synthesis. As such, we instead adopted a more narrative literature review approach. Unlike systematic reviews, narrative literature reviews do not attempt to comprehensively identify all relevant literature on a particular topic [18]. Instead our aim was to (1) intentionally explore particular issues that are established as important in relation to ICT in general but are overlooked by existing reviews into the energy use implications of 5G, in order to (2) provide an assessment of whether these themes are being overlooked by the literature on the energy use implications of 5G and highlight their potential importance.

The first stage of the review process involved a close reading of existing reviews on the topic of green, sustainable and energy efficient future mobile networks. Not only did these reviews yield a large number of relevant studies, this task also identified a number of apparent blindspots in the consideration of the energy use implications of 5G. On the basis of these gaps (as discussed in section 2 above), we intentionally searched for studies that took a whole network approach and that focused on embodied energy and indirect energy use impacts. This deductive approach to establishing these issues as significant themes worthy of investigation was informed by the broader literature on the energy use of ICTs and especially the taxonomy of ICT energy effects offered by Horner et al. [19]. Amongst the various indirect and higher order effects of ICT on energy use, we narrowed our focus to just direct rebound effects and enablement effects (ignoring indirect rebounds, economy-wide rebounds and systematic transformation). This was partly due to space constraints and the need to manageably bound the research focus, but also because these effects strike us as having an obvious yet underexplored influence on the energy use implications of 5G, as being relatively more easily quantifiable, and as being most directly the responsibility of 5G (and as such something those advocating for the energy saving potential of 5G ought to take account of).

Using Scopus, Google Scholar and IEEE Xplore[1], searches were conducted for studies on specific technologies highlighted by the existing reviews, studies from a whole network perspective, and studies that included a focus on embodied energy and rebound and enablement effects. Google searches were also used to identify studies from relevant companies, industry bodies, market analysts, government agencies, and NGOs. Where searches on 5G specifically yielded few results, we expanded our focus to mobile networks, then telecommunications networks, then ICT in general. When searching for studies from a whole network perspective we expanded our scope to mobile networks; whereas when searching for work with a focus on embodied energy, rebound effects and enablement effects we expanded our scope to ICT in general. This approach enabled us to identify areas of insufficient research focus and publicly available evidence in relation to 5G, and to identify studies on related but more general topics that demonstrate the potential significance of the issues currently underexplored in relation to 5G.

Many different combinations of search terms were used, including varying terms for the case scope (5G, mobile networks, telecommunications, ICT), the general topic (energy, energy use, energy

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[1] The initial scoping searches and the existing reviews had made clear that a large number of relevant studies are published in the journals of the Institute of Electrical and Electronics Engineers.

efficiency, energy consumption, green, sustainable, environment, environmental impact, carbon footprint, climate change) and theme of interest (particular technologies; whole network, holistic, network-wide, national, country-wide; lifecycle, life cycle, LCA, embodied energy; rebound effect, indirect effects, second order effects, higher order effects, user behaviour, consumer behaviour, consumer demand, behaviour change, demand-side, demand-side management; enablement effect, vertical, vertical industries). Studies that were identified through these search strings were screened for relevance on the basis of their title and abstract (i.e. did they report findings related to the energy use of 5G and future mobile networks, or the embodied energy and indirect effects of ICT more broadly) and relevant papers were screened for significance on the basis of a reading of the full paper (i.e. did the findings they report have important implications for understanding the potential energy use impacts of particular technologies associated with 5G and of future mobile networks in general from a whole network perspective, or for understanding the potential significance of embodied energy and indirect energy effects).

This approach yielded a large number of simple, small-scale, single-technology assessments. Many of these studies had already been covered by the existing reviews discussed in the previous section so we do not include these studies in our findings. Instead, we simply explain what the key technologies are as part of the previous section. This approach yielded just four whole network assessments of the energy use impacts of 5G and future mobile networks (presented in section 4.1.1), as well as a number of studies that demonstrate the importance of embodied energy, rebound effects and enablement effects in the broader context of ICT (presented in sections 4.1.2, 4.2.1 and 4.2.2 respectively).

4. Results: Exploring direct and indirect energy use impacts

In this section, we first explore direct energy use impacts of 5G from a whole network perspective, before turning to the largely overlooked but potentially significant embodied energy associated with mobile networks. We then move to examine the possible significance of indirect energy use impacts, namely rebound effects and the enablement effect.

4.1 Direct energy use impacts

In this initial findings section we focus on studies into the direct energy use impacts of future mobile networks. By direct energy use impacts we refer to the energy used in the production and use of mobile networks, as opposed to any subsequent (indirect) effects mobile technologies may have in changing user behaviour or the way other industries operate. Whilst a large number of simple, small-scale, single-technology assessments have been conducted into particular energy efficiency technologies associated with 5G, such studies have already been well covered by the existing reviews discussed in section 2. Instead, we focus on approaches and areas of focus that have largely been overlooked by existing reviews. As such, this section is split into two subsections with the first focusing on studies that take a whole network approach to assessing the operational energy use of 5G and future mobile networks and the second detailing the potential importance of the embodied energy impacts largely overlooked by both the existing reviews and the whole network studies considered in the following section.

4.1.1 Whole network assessment

Whole network perspectives attempt to assess the impact of a range of technological interventions in a model network that spans a large and diverse geographical area (i.e. a model that seeks to replicate as far as possible the scale and complexity of a ‘typical’ national mobile network). This involves networks that cover rural, suburban and urban areas, with traffic profiles varying over both space and time. They therefore seek to give a realistic impression of the energy use or carbon footprint of future networks, rather than merely assessing the possible energy saving contribution of a particular technology. We first consider studies that estimate mobile network energy use up to 2020 (‘near-historical assessments’, section 4.1.1.1), and then move on to studies that forecast energy use or carbon emissions beyond the present-day (‘future assessments’, section 4.1.1.2). The whole network assessments we identified are summarised in Table 2.

4.1.1.1 Near-historical assessments

The GreenTouch consortium’s 2010-2015 Green Meter project assessed how to improve the energy efficiency of communications networks (i.e. including core networks, fixed access networks, and mobile networks) [20]. Using traffic volumes and patterns based on a mature telecommunications market, this project concluded that a combination of technological interventions could result in a 99% reduction in the energy consumption of a national mobile network in 2020 compared to a state-of-art 2010 reference case.

In particular, three combinations of technological interventions were proposed. *Beyond cellular green generation* involves a combination of the decoupling of signalling and data functions, BS sleeping strategies and the use of small cells to dynamically extend network capacity when required in hotspot areas as part of a HetNet. *Large-scale antenna systems* (i.e. M-MIMO) feature small, low power, individually controlled antennas which direct data-bearing beams to multiple users simultaneously and use an adaptive algorithm to achieve further energy efficiency gains by optimally providing varying levels of service to users. *Green transmission technologies* relate to the trade-off between energy efficiency and spectral efficiency (b/s/Htz), and aim to adapt the network toward maximising energy efficiency whenever possible to do so whilst maintaining QoS.

After testing the efficiency of these technologies across the various traffic environments and dynamically altering the approach according to temporal variations, GreenTouch selected the most efficient approach for each environment. The average energy efficiency of the 2010 reference based on a mature market scenario is 5850J/MB, yielding an energy consumption of 25TWh/year. The optimum combination of the GreenTouch technologies discussed above applied dynamically across various environments leads to a 10,000-fold improvement in energy efficiency versus the 2010 reference case, resulting in an energy consumption of less than 1% of the 2010 reference despite a 89-fold traffic increase. It is worth noting that all of these scenarios envisage the large-scale swap out of equipment between 2010 and 2020.

In 2013, the EARTH project estimated the carbon footprint of global mobile communications between 2007-2020 [21]. Using a lifecycle analysis approach, they estimated that under a ‘continuous improvements’ scenario the carbon footprint of mobile communications would be 235MtCo2e in 2020, up from around 87MtCo2e in 2007. This scenario assumes that historical 8% annual energy efficiency improvements in RAN equipment will continue throughout the timescale studied. A worst-case ‘no improvements’ scenario sees emissions rise more than threefold from 2007 to hit around 288MtCo2e in by 2020. This analysis includes the manufacture and operation of mobile phones; the manufacture, construction and operation of RANs; operator business activities; and data centres and data transport. Whilst RAN operation was estimated to be responsible for the largest proportion of emissions in 2007 (45%), the manufacture of mobile phones becomes increasingly significant up to 2020 and is responsible for a similar proportion of emissions to RAN operation by 2020 (around 30% each).

Following their estimate of the global carbon footprint of mobile communications out to 2020, the EARTH project then homes in on the operational energy used by RANs. Of course, their own assessment suggests that by 2020 RAN operational energy use will account for 30% of the total carbon footprint of mobile communications and that mobile phone manufacturing emissions will be equally significant. Nonetheless, the aim of the project is to decrease the operational energy consumption of RANs by 50% without degrading QoS. Because the remainder of their analysis focuses only on the operational energy used by RANs, the energy use associated with the manufacture and construction of BS sites, the manufacture and use of user devices and the operation of data centres are not included in their assessment of the energy savings that are possible.

They find that in the ‘continuous improvements’ scenario, the annual global operational electricity consumption of RANs increases by 28% between 2012-2020 (from 77 TWh to 99 TWh), given a 1000-fold increase in traffic. They find that under a ‘new technologies’ scenario - in which all BSs deployed between 2013-2020 use 50% less electricity on a per-site-average basis - electricity consumption increases slightly between 2012 and 2020 (from 77 TWh to 86 TWh, a 13 TWh saving versus the 2020 figure for the ‘continuous improvements’ scenario). This 50% per-site-average reduction in electricity consumption is achieved through a combination of hardware solutions, radio interface techniques and network level solutions (see Table 1). Finally, a ‘large-swap out of equipment’ scenario, in which 40% of already installed BS sites are replaced by state-of-the-art equipment between 2013-2020 in addition to the improvements discussed as part of the ‘new technologies’ scenario, sees electricity consumption fall to 48 TWh by 2020 (compared to 49 TWh in 2007 and 77 TWh in 2012, a 50% reduction relative to the 99 TWh figure for the ‘continuous improvements’ scenario in 2020).

Tombaz et al. 2016 simulate the energy use of a 2020 5G network for a typical European country over a 24hr period and compare it to a 2014 LTE network in the same modelled country but serving four times less traffic [22]. They therefore consider the hypothetical case in which all 4G BSs are replaced by 5G BSs (i.e. the 5G BSs are simply swapped into the same sites, so no densification is considered). The key differences between the networks are the more frequent, longer and deeper sleeping possible in 5G (due to the separation of signalling and data functions); and the use of massive, user specific beamforming (which increases throughput enabling traffic to be served more quickly resulting in more opportunities for sleeping). Their results show that the average power per area unit for the LTE network is 0.14 kW/km2 compared to 0.06 kW/km2 for 5G. This represents a 55% energy saving whilst serving four times as much traffic and improving user performance and system capacity.

Comparisons between the near-historical forecasts covered here and actual network energy consumption should be treated with caution for number of reasons, however we provide a brief comparison here in order to provide a sense of how actual network energy consumption is estimated to have unfolded over the period covered (i.e. up to 2020). The reasons for caution when making such a comparison include the fact that two of the studies above are not actually attempts to forecast the future energy use of mobile networks but, in the case of GreenTouch, an attempt to identify the maximum technically achievable energy efficiency improvements; and in the case of Tombaz et al., a hypothetical scenario designed to illustrate the energy efficiency of 5G compared to 4G. Furthermore, the studies above have different geographical scopes. Whilst EARTH’s forecast is for the global operational electricity use of RANs, the findings of GreenTouch and Tombaz et al. are based on particular types of modelled networks (a ‘developed market’ network in the case of GreenTouch and a ‘typical European’ network in the case of Tombaz et al.).

Malmodin and Lunden provide an estimate of the global operational electricity use of mobile networks in 2015 [23]. They use measured data from 10 operators with operations across 30 countries, which they supplement with publicly available data for four other major operators and one country-wide dataset. They then extrapolate to the global level by using average electricity consumption per substruction and the number of subscriptions not covered by their dataset. They estimate that the operational electricity use of global mobile networks in 2015 was 110 TWh, up from 73 TWh in 2010. These figures are for grid electricity only, they estimate that in 2015 mobile networks consumed a further 27 TWh of on-site generated electricity. The system boundary they adopt for the mobile network is, however, not directly comparable with the EARTH project. Whilst the EARTH project forecasts the operational electricity use of global RANs, Malmodin and Lunden include the electricity use of various operator activities as well as the RAN. The International Energy Agency produce a similar figure of around 120 TWh for the electricity use of mobile networks globally in 2015 [24]. Whilst the report is not clear on the exact system boundaries used, we assume that this estimate is for core, transmission and access networks, rather than just the RAN. As such, we assume that the same issue of system boundary incompatibility applies in relation to EARTH's forecast.

Coroamă offers an estimate for global RAN energy consumption for 2020 of 100 TWh [25]. The estimate is a 'fair approximation' based on a review of existing assessments that attempts to harmonise estimates of RAN energy intensity with assessments of RAN energy consumption. This is based on the simple principle that energy intensity (TWh/EB) x traffic (EB/year) = energy consumption (TWh/year), and the view that reliable estimates exist for traffic. Interestingly, this estimate is very comparable to EARTH's continuous improvements scenario (99 TWh) which assumed that historical 8% annual energy efficiency improvements in RAN equipment would continue between 2012-2020. It is, of course, significantly higher than EARTH's best-case 'large scale swap out of equipment' scenario (48 TWh).

4.1.1.2 Future assessments

STL partners[2] estimate the emissions saving potential of various 5G roll-out scenarios compared to a 'No 5G' scenario [26]. They argue that the emissions saving potential of 5G comes from both core network and RAN improvements (including beamforming, M-MIMO, sleep modes, and the millimetre wave spectrum). They estimate that these 5G technologies could result in 2030 5G mmWave RANs consuming under 2% of the energy usage per bit transmitted of a 2018 3G/4G RAN. As such, the speed of 5G roll-out determines the scale of savings achieved [26]. They estimate that, without 5G (but including the some 4G improvements and grid decarbonisation) the cumulative emissions of global mobile networks (operational emissions of the core network and RAN) between 2020-2030 will be 4,750Mt CO2[3]. A slow 5G roll-out scenario leads to cumulative emissions of 3,880Mt CO2 over the same timescale, the base case medium roll-out results in 3,100Mt CO2, and a fast roll-out results in 2,590Mt CO2. The fast roll out scenario therefore represents a 45% reduction in cumulative CO2 emissions compared to the no 5G scenario, whilst the base case medium scenario leads to a 35% reduction.

In terms of the annual carbon footprint of global mobile networks, the fast roll-out is the only scenario that results in lower annual emissions in 2030 than 2018, with annual CO2 emissions dropping by about 30Mt by 2030. The base case scenario sees annual CO2 emissions rise by around 50Mt between 2018-2030. The slow roll-out scenario results in annual emissions increasing by

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[2] STL partners are an independent consulting and research firm. The research was supported by Huawei.

[3] The report is not clear whether the metric is CO2 or CO2e. In this particular case CO2 is used, but elsewhere in the report CO2e is occasionally mentioned without a clear explanation of the relationship.

around 100Mt by 2030. Finally, the no 5G reference case sees annual CO2 emissions 390Mt higher in 2030. The fast roll-out scenario involves 5G launching around the world between 2019-2021, 5G serving 99% of mobile traffic in advanced economies by 2030 and high roll-out of millimetre wave cells. For comparison, the base case medium roll-out scenario sees 5G launching between 2019-2022, with 60% of mobile data running over 5G by 2025, and 85% by 2030.

Beyond the STL partners report, there are a number of industry reports that provide assessments of the energy use of future mobile networks, including the implications of 5G deployment. We do not include these reports in table 2 below because of a lack of detail about methods and key assumptions. We do however discuss them briefly here in order to provide a flavour of the expectations of some key industry players. For example, in a 2016 white paper Nokia suggested that “we can be confident that operators will be able to reduce their power consumption in the future” [27]. This is based on a scenario in which ‘a European operator’ can expect to see network energy consumption fall to 70% of 2015 levels by 2025. This occurs in a scenario which sees traffic grow at 58% annually, energy saving features implemented to 4G between 2020-2025, and 5G launched in 2020. The energy saving potential in this scenario arises from 5G sleep modes as well as improved hardware and greater small cell deployment in both 4G and 5G.

Further examples come from Ericsson’s 2020 ‘Breaking the energy curve’ report [28] and an internal analysis by Vertiv (a digital infrastructure provider) [29]. Ericsson suggest that it is possible to quadruple data traffic without increasing network energy consumption by modernising existing infrastructure, activating energy saving software, optimising 5G network performance and using AI to operate infrastructure intelligently. Vertiv, on the other hand, estimated in 2019 that “the move to 5G is likely to increase total network energy consumption by 150-170 percent by 2026” [29]. However, in both cases, there is a lack of publicly available detail about the methods, assumptions and data that these estimates are based on.

Whilst we certainly do not mean to suggest that these industry figures are in any way unreliable, it would be preferrable if they were supplemented by more peer-reviewed assessments of the energy use of future mobile networks (including the implications of 5G deployment) that provide fuller disclosure of the data, assumptions and methods used in order to enable proper scrutiny from the wider research community.

Table 2: Whole network estimates of the impact of 5G on energy use

Study	Intervention assessed	Baseline	Scope	Method	Metric	Improvement timeline	Estimated traffic increase	Findings
GreenTouch [20,30]	3 combinations of interventions: 1. Beyond cellular green generation 2. Large scale antenna systems 3. Green transmission technologies	A modelled 2010 network with traffic volumes and state-of-art LTE (i.e. 4G) equipment from that year; 4 competing operators Note this modelled network is more energy efficient and provides better coverage than actual networks did in 2010	Operational electricity use of RANs, modelled on developed markets (W. Europe, N. America & Japan)	Traffic models based on reported traffic per user per month in 2010, with growth trends extrapolated to 2020; different traffic models for four geographic area types (rural, suburban, urban, dense urban) Developed BS power models that forecast power consumption for different types and configurations, hardware component trends also modelled Operator data used to build deployment model, including heterogenous	Energy efficiency (GB/TWh); energy consumption	2010 -2020	x89	Energy efficiency improvement factor of x10,000, a 99% reduction of energy consumption

				traffic demand (i.e. hotspot areas) Energy efficiency simulations were run for various area types and traffic loads; network architectures and types and densities of BSs were varied to identify the optimum approach for different contexts Operator network sharing assumed in 2020 scenario				
EARTH [21,31,32]	Hardware solutions – antenna hardware, macro-cell hardware, small-cell hardware Radio interface techniques – bandwidth adaption, beamforming,	Two 2020 scenarios subject to the same levels of traffic demand – ‘no improvement’, ‘continuous improvement’ (a continuation of the historical trend of 8% yearly efficiency	Global RAN operational electricity use	Small-scale, short-term evaluations were conducted for various deployment environments (rural, suburban, urban and dense urban) with realistic traffic loads for each environment at various times of	Energy consumption (TWh)	2007, 2012 - 2020	x1,000	50% reduction in the annual global electricity consumption of RANs - 2020 continuous improvements scenario (99 TWh) vs 2020 ‘large swap out of equipment’ scenario (48

	antenna muting, sleep/DTX, power control Network level solutions – macro-cell, small-cell, relay, multi-radio access technology, scheduling/radio resource management	improvements in RAN equipment)		the day BS power models were informed by hardware and software prototyping, and sleeping strategies were validated using Telecom Italia's test plant Daily traffic profiles for each environment were used to generate the power consumption over a day (i.e. summing the short-short evaluations proportionately to typical daily traffic cycles) Large-scale system energy consumption was derived based on a typical mix of different environments types				TWh) Annual global RAN electricity consumption in 2020 for various scenarios (TWh): No improvements – 109 Continuous improvements – 99 New technologies – 86 Large scale swap out of equipment – 48

Tombaz et al. [22]	Decoupling system functionalities and user data related functionalities; and associated improvements in DTX occurrence, duration and depth Massive beamforming	2014 LTE	Operational electricity use of a nationwide RAN over a 24hr period, modelled on a typical European country (Austria)	Existing datasets used to model population densities and share of population living in each environment for 6 environment types (super dense urban, dense urban, urban, suburban, rural, and wilderness) Traffic demands (MBps/km2) in each environment estimated for 2014 and 2020 using population densities, forecasts for penetration rate of different devices, average monthly usage of each device, activity rate of users during busy hour (giving the peak traffic demand) and a daily traffic fluctuation model	Daily averaged area power consumption (kW/km2) (preferred to J/bit because the latter can highlight an improvement in efficiency whilst obscuring an increase in energy consumption)	2014-2020	x4	55% energy saving (average area power consumption of 0.14kW/km2 vs. 0.06kW/km2)

				(giving the daily traffic profile based on the peak demand) The network was then modelled, ensuring that maximum traffic demand and performance requirements were met. Country-scale results achieved through the weighted summing of the results for each environment given the proportion of the country covered by each environment				
STL Partners [26]	Core network improvements, RAN improvements (beamforming, M-MIMO, sleep modes, Millimetre wave spectrum)	No 5G and slow 5G roll-out scenarios	Global; operational electricity use of core networks and RANs	Projections for data volumes for each country, and actual figures for energy consumption of core networks and RANs used to establish 2018	Emissions (Mt CO2), network energy efficiency (GWh/EB)	2018, 2020 - 2030	Not stated, varies by country	2030 5G (without mmWave) improves energy efficiency by 90% compared to 2018 networks

				network efficiency (i.e. energy consumption divided by 2018 data volumes) Theoretical maximum efficiency of 5G technology inferred from a range of sources including interviews with industry Theoretical energy efficiency projected for each year under different scenarios (with different rates of 5G market share and efficiency improvements) x projected data volume for that year gives yearly energy consumption for each country				(3G/4G mix) 2030 5G with mmWave improves energy efficiency by over 98% compared to 2018 networks Approximate annual CO2 emissions of mobile networks globally in 2030 under different scenarios in Mt CO2 (compared to ~ 205 in 2018): No 5G roll-out ~ 600 Slow 5G roll-out ~ 300 Medium 5G roll-out ~ 260 Fast 5G roll-out ~ 190 Cumulative global CO2

				Yearly network energy consumption x CO2 footprint per unit of electricity for each country				emissions from mobile networks 2020-2030 (Mt CO2): No 5G = 4750 Slow = 3880 Medium = 3100 Fast = 2590

4.1.2 Embodied energy and lifecycle assessments

As well as the electricity use associated with operating mobile networks, direct energy use impacts also occur throughout the rest of the life cycle of mobile networks, including the energy use associated with the manufacture and disposal of network equipment and user devices. Notwithstanding some notable exceptions (for example, [33,34] as discussed below), as demonstrated in both sections 2 and 4.1.1, these so-called embodied energy impacts tend to not be included in assessments of the energy use impacts of future mobile networks. In this section we therefore explain these impacts, review studies that have assessed them in the broader contexts of telecommunications and ICT, and point out their potential significance in relation to 5G.

Lifecycle assessment (LCA) refers to a tool for assessing the environmental impacts of a product or service throughout the whole lifecycle from raw material acquisition to the production and use phases to waste management [35]. LCAs can be used to assess the environmental impacts of single products or services, or to compare the environmental impacts of products or services that fulfil a similar function (e.g. the environmental impacts of streaming music versus buying music as physical media) [35].

Embodied energy is "the energy consumed by all processes associated with the production of a device" [33]. Humar et al. further distinguish initial embodied energy and maintenance embodied energy, where the former relates to the energy used in acquiring and processing raw materials, transport, manufacturing devices and installing equipment; and the latter refers to the energy used in maintaining, repairing and replacing equipment over the course of its lifetime [33].

Lifecycle analysis has been widely deployed in relation to ICTs in general. In their review of LCAs of ICT products and services since 2000, Arushanyan et al. identify 60 studies [35]. They find a strong focus on single consumer goods (especially PCs, albeit with certain blind spots such as games consoles) and on comparisons between ICT-based and conventional activities, with relatively less attention paid to network infrastructure. Generally speaking, the use phase of larger, longer-lasting, 'always on' network infrastructure tends to dominate; whereas for smaller, energy efficient devices (e.g. mobile phones) the manufacturing phase becomes more significant. Arushanyan point out that assumptions made about user behaviour (e.g. hours of use, years in use, approach to disposal/recycling, etc.) often have an important influence on the findings of such studies, however user behaviour remains under-discussed and a better understanding of different patterns of user behaviour and their impact on the environmental effects of ICTs is required.

Hischier et al. assess the 'grey energy' consumed by PCs, laptops and tablets and the network infrastructure required for these devices to access the Internet [36]. Grey energy is a very similar concept to embodied energy but relates specifically to the non-renewable energy consumption throughout the lifecycle of a product or service. Generally, they find that the production phase becomes more significant the smaller and more energy efficient a device becomes. When taking into account the production and use of the infrastructure required to access the internet (customer premises equipment, access networks, edge and core networks, and data centres), they find that this network infrastructure has a greater impact the smaller the device. For instance, the production and use of this network infrastructure accounts for over 90% of the grey energy consumed by downloading 1MB of data on a tablet computer.

Cooper et al. apply an LCA to estimate the GHG emissions impact of the use of four device types (PCs, laptops, tables, smartphones) by an individual in the UK over a year [37]. They focus on the creation and use phases but exclude the end of life phase. Their 'user-centric' approach includes collecting primary data from 200 individuals through an online survey about their ICT use. Using their primary user behaviour data, they derive a series of user types and their usage patterns over prototypical days (i.e. days that usually have similar usage patterns, for instance weekdays and weekend days). They then use this alongside LCA data for the manufacture and use of these devices to estimate that the impact of one average UK individual using these devices over a year is 123.7kg Co2e for the use phase and 127.1kg Co2e for the creation phase.

Malmodin et al. perform an LCA of TeliaSonera's Swedish ICT network over a year of operation (2009), which they then scale up to give a national figure for ICT in Sweden [38]. Furthermore, they use a global average electricity mix to give a sense of the lifecycle impacts of ICT networks globally. The parts of the network covered are the manufacturing and use of PCs and other user equipment, access networks, core networks and data transmission, data centres and local area networks, and operator activities. Overall, they estimate that TeliaSonera's ICT network had a carbon footprint of 0.65 Mt CO2e, from which they extrapolate a figure of 1.5 Mt CO2e for ICT in Sweden as a whole. The key contributions to these footprints come from the manufacturing of PCs and other user equipment (due largely to these devices being manufactured in countries with more fossil fuel based electricity generation than Sweden), the manufacturing and construction of access networks, and the operation of data centres and local area networks. Using a global average electricity mix (which has a carbon intensity x10 higher than Sweden – 0.6kg CO2e/kWh vs. 0.06kg CO2e/kWh) leads to a much higher carbon footprint, with a higher proportion of emissions from the operational electricity use of user devices, access networks and data centres due to the more carbon-intensive grid.

Interestingly for the purpose of our discussion here, as part of their calculations Malmodin et al. estimate that 2G and 3G base stations have an annual manufacturing carbon footprint (i.e. total embodied energy shared by lifetime) of 3.5 kg CO2e per average subscriber. This figure assumes a lifetime of between 7 and 20 years, relates to the average BS site installed in Sweden prior to 2005, and is based on an earlier LCA performed by Ericsson. For a 3G BS this compares to an annual operational electricity use carbon footprint of 1.4 kg Co2e per average subscriber using Sweden's generation mix and 14 kg Co2e for the global mix. On the basis of these figures, embodied energy is responsible for around 70% of the total annual carbon footprint of a 3G BS in a low-carbon electricity mix context (i.e. Sweden) and 20% in a more typical context (i.e. the global average electricity mix) (see Malmodin et al. 2014a).

As already seen, the EARTH project employed an LCA to estimate the global carbon footprint of mobile networks [31]. This included emissions from the manufacture and operation of mobile devices; the manufacture, construction and operation of RAN infrastructure; operator activities (offices, stores, vehicles, travel); and data centres and data transport (the use of other network resources based on the data traffic generated by mobile users). As discussed above, they estimate that the global carbon footprint of mobile networks will be 235Mt Co2e in 2020 (up from an estimated 86Mt Co2e in 2007). They estimate that, by 2020, mobile device manufacturing will have the highest share of emissions (30%), compared to RAN operation (29%) and data centres and data transport (19%). They also estimate that the manufacture and construction of RAN infrastructure will remain fairly insignificant in comparison.

As seen in sections 2 and 4.1.1 above however, assessments of the direct energy use impacts of 5G have excluded the energy use associated with either the manufacture and disposal of user devices; or the construction, manufacture, maintenance and replacement of network infrastructure (e.g. BSs). Humar et al. suggested that whilst a number of studies into the energy use of mobile networks had suggested embodied energy as an important topic for future research, at that time, to their knowledge, no studies had actually investigated the issue [33]. According to Humar et al., overlooking embodied energy in assessments of the energy use of mobile networks is perhaps especially problematic because embodied energy is likely to be particularly significant for mobile networks compared with other technological domains. This is because the pace of technological improvement means that devices and equipment become obsolete quickly meaning that their lifespans are relatively short. This is exacerbated by the highly technical nature of manufacturing certain components used in BSs [33].

Seeking to fill this gap, and assuming that an average macro BS has a lifetime of 10 years, Humar et al. estimate that the operating energy use of a BS is 150 GJ compared to an embodied energy use of 85 GJ. As such, they found that embodied energy accounts for 36% of the total energy consumption of a BS over its lifetime. Furthermore, Humar et al. run a simple simulation of a network in an urban area with varying numbers of BSs in order to explore the trade-off between operational and embodied energies. They find that, as the number of BSs increases, the energy efficiency (J/bit) of the network becomes significantly lower when taking embodied energy into account than when ignoring embodied energy. For example, when there are 40 BSs in the 5km area, the network is less than half as energy efficient when taking embodied energy into account than when ignoring it. Their work also suggests that the optimum number of BSs in this network when ignoring embodied energy and utilising a sleeping strategy is over 60, compared to an optimum of around 15 when taking embodied energy into account. Moreover, when taking embodied energy into account, the energy consumption of the supposedly optimum (whilst ignoring embodied energy) 60+ BS network increases by over a factor of 3. This work has particularly troubling implications for the energy saving potential of ultra-dense HetNets. There is an obvious trade-off between saving operational energy through increasing the number of BSs in a HetNet scenario (through lower power micro-BSs and shorter transmission distances) and the embodied energy required to produce, install and maintain the additional BSs required. However, work considering the energy saving potential of ultra-dense HetNets tends to consider only the operational energy saving without accounting for the increase in embodied energy associated with this strategy.

Furthermore, this work also raises questions about the effectiveness of sleeping strategies once embodied energy is taken into account, as to some extent these schemes depend on having a large number of BSs in order to dynamically adapt the network in accordance with traffic demands. Sleeping strategies could lead to BSs that were manufactured at the cost of significant embodied energy spending a high proportion of their operational lifetime switched off in order to save operational energy, with this approach justified on the basis of assessments that only considered the latter form of energy use [33]. Considering embodied energy is therefore clearly important because its inclusion has the potential to alter the relative merits of different energy saving strategies. For instance, taking embodied energy into account may lead us to prefer M-MIMO (increasing the number of antennas) over BS densification (increasing the number of BSs).

More recently, Chan et al. used real network data from the California Research and Education Network (a state-wide research and education network) to model the interdependencies between embodied energy, operational energy, network traffic growth and efficiency improvements in both the operational and embodied phases between 2016-2025 [34]. Under current trends of efficiency improvements in both operational and embodied phases and traffic growth, they find that the optimal equipment replacement cycle (i.e. the approach to upgrading the network that leads to the lowest total energy consumption from both embodied and operational energy) is between 5-10 years. They also find that, due to the current relatively slower rate of efficiency improvement for the embodied phase, as the rate of traffic growth increases, embodied energy accounts for an increasing share of the total network energy use. Finally, they also find that the relative rates of embodied and operational efficiency improvements are also important. When there are strong improvements in embodied energy efficiency, shorter equipment replacement cycles can reduce the overall network consumption due to the relatively lower energy cost of upgrading the network with state-of-art equipment. However, where embodied efficiency improvements lag operational efficiency improvements, this acts to restrict the operational energy reductions that can be achieved (due to the high embodied energy cost of installing more operationally efficient equipment). As such, Chan et al. argue that “ technological advances in both operational and embodied energy efficiency should be achieved hand-in-hand in order to make future telecommunication networks sustainable” [34].

Embodied energy is significant because the scenarios presented above that report energy savings associated with 5G do so on the basis of the large-scale installation of state-of-art 5G network infrastructure (either in addition to or replacing older equipment). However, the embodied energy use associated with this new equipment has not been accounted for, meaning that the reported findings overstate the energy saving potential of 5G from a lifecycle perspective. According to Humar et al.’s admittedly decade old analysis, the embodied energy of a BS over a 10 year lifetime could amount to around a third of its total energy consumption [33]. A key question to be addressed therefore is what proportion of the headline savings reported above is cancelled out by the energy use associated with the manufacture of 5G enabled devices (IoT devices and smartphones) and the replacement of or addition to existing network infrastructure with 5G equipment? The work of Humar et al. makes clear that we should be sceptical about energy saving strategies that rely on the largescale swapping in of new hardware, especially when the embodied energy of this hardware is not accounted for in the assessment of the energy saving potential of such strategies. The work of Chan et al. suggests that, under current trends of efficiency improvements and traffic growth, embodied energy is set to account for an increasing share of the total energy consumption of networks, and that greater attention needs to be paid to improving the embodied energy efficiency of network infrastructure alongside the operational energy efficiency of networks.

4.2 Indirect energy use impacts

Beyond the direct operational and embodied energy use related to mobile networks discussed above, 5G is also expected to have indirect energy use impacts. Such impacts are considered ‘indirect’ because rather than relating to energy use in the production and operation of mobile networks, they relate to 5G-driven energy use changes in user behaviour and in other sectors of the economy. These indirect energy use impacts have not yet been widely studied in relation to 5G specifically. Therefore, our approach here is to explain each effect in turn, highlight the impact of such effects in relation to telecommunications or ICT in general, and emphasise the potential significance of these effects in relation to 5G.

4.2.1 Rebound effects and user behaviour

Rebound effects occur when efficiency improvements lead to greater demand for the same (direct) or other (indirect) products or services. As Hilty et al. put it “[i]f some good or service can be produced with higher efficiency, i.e., more useful output can be generated per unit of input, the good or service may become cheaper or more convenient to use, which in turn can result in higher demand for that good or service, or for something else that becomes affordable due to the saved money or time” [40]. Whilst we focus narrowly on direct rebound effects, Bjorjesson Rivera et al. have offered a typology of ‘second order’ effects linked to ICT including economy-wide rebound effects and time rebound [41], and Hilty et al. distinguish longer-term systematic effects due to changes in practices of consumption and structures of production [40].

Considering rebound effects is important because they can temper the energy saving potential of a technology that increases energy efficiency. In extreme cases, they can even lead to 'backfire' (i.e. efficiency improvements leading to an increase in total energy consumption) [42]. Rebound effects also demonstrate that technological advances that improve energy efficiency are "a necessary, but not sufficient condition for saving resources" [43].

We consider user behaviour alongside rebound effects because rebound effects relate to the question of how users respond to a new technology (i.e. how they respond to increases in efficiency from a new technology leading to monetary or time savings). All attempts to assess technologies and strategies aimed at reducing the energy use of mobile networks must take some aspects of user behaviour into account (e.g. the number of users in a particular cell, whether they're stationary or moving, their traffic demands, etc.). Furthermore, some technology-centric studies seek to exploit user behaviour in order to reduce energy demand – for example, D2D relies on the relative position of users in space, whereas certain caching strategies use knowledge and predictions about popular content to store that content closer to the user and so prevent unnecessary traffic [44,45]. However, by user behaviour we refer here to 'user-centric' approaches that seek to understand practices and patterns of connected device (e.g. mobile phone) use, their implications for the energy use of mobile networks, and the way the changing practices and patterns of device use may impact data and energy demand. Such knowledge about how devices are used and the energy use implications of this may be used to develop energy-saving technologies and strategies (e.g. caching strategies) or to identify and encourage user practices that use less energy.

As such, the potential for 5G to reduce energy consumption depends not only on the technological capability to improve the energy efficiency of mobile networks, but also on how consumers respond to per-bit price reductions associated with such efficiency improvements, and how, if at all, mobile operators or policy-makers seek to shape this response. There is a lack of consideration about how 5G could lead to rebound effects, possible user behaviour changes with energy use implications in response to the introduction of 5G, and how policy might seek to prevent damaging rebound effects. In fact, on the basis of a systematic literature review of studies on the indirect environmental effects of ICT, Bieser and Hilty argue that the consumption side (i.e. studies using consumer-centric methods to assess how ICT changes consumption patterns) is underexplored for ICT in general [46]. Similarly, in a systematic review of LCAs of the environmental effects of ICT, Pohl et al. (2019) found that studies predominantly focused on the technology-focused effects of optimization and substitution, rather than user-focused rebound effects [47]. Furthermore, in a systematic review of the energy consumption impacts of the digitisation of goods, Court and Sorrell find that rebound effects are largely ignored; and whilst results are sensitive to assumptions about user behaviour, this is rarely empirically studied [48]. Finally, in a review of the 10 most influential studies assessing the CO2 emissions of ICT, Erdmann and Hilty found that most did not attempt to take rebound effects into account [49].

A number of studies have nonetheless explored rebound effects in the context of ICT. For instance, Joyce et al. use a multi-regional input-output analysis to explore the indirect rebound effects associated with three scenarios in both Sweden and the EU (a reduction in spending on ICT leading to increased spending across all product groups, a reduction in spending on electricity leading to increased spending across all product groups, and a reduction in spending on electricity leading to increased spending on ICT) [50]. For scenario one, across three environment impact measures (GHG emissions, total energy use, total material footprint), they find backfire effects for both Sweden and the EU. On the other hand, rebound effects from reduction in spending on electricity (i.e. scenarios 2 and 3) are more modest and in Sweden (2-67%) and especially the EU (5-9%) due to the latter's more fossil fuel intensive grid (i.e. reduced spending on electricity gives a greater environmental benefit than in Sweden due to the fossil fuel intensive grid, so larger rebounds are required to cancel out this large initial improvement).

In their systematic review on the energy and climate impacts of teleworking, Hook et al. found that more rigorous studies with wider scopes tended to find smaller energy savings from the work travel avoiding through teleworking, with some of these studies even finding increases in energy use [51]. The reason for this was that these studies were more sensitive to potential rebound effects and complex changes in behaviour in the form of longer commutes on work travelling days due to part-time teleworkers feeling able to live further from their workplaces and greater non-work travelling (e.g. more dedicated non-work trips, or opportunistic trips utilising the time freed up by the lack of a commute).

Some studies have focused on user behaviour with a view to identifying strategies to influence user behaviour in order to reduce ICT energy use. Whilst this sort of demand-side management is fairly commonly employed in relation to electricity use in the home (e.g. discouraging unnecessary electricity use, or encouraging use at off-peak times) it is less commonly raised in relation to the use of digital services. However, Morely et al. argue that “[c]ontaining the overall growth in energy demand across digital infrastructures… depends on more than efficiency alone: it requires limiting the growth in traffic, to at least keep in step with efficiency improvements, a balance which has not so far been the case” [52].

For example, Priest and Shabajee (2010) argue that it is questionable whether sufficient energy efficiency improvements required to ensure that demand for downloaded data remains sustainable are achievable. As such, they suggest behaviour change strategies such as reducing digital waste, persuasive design, raising awareness of usage and time shifting of streamed media [53]. Meanwhile, in a longitudinal study of student’s ICT user behaviour in a computer teaching lab, Yu and Bhatti find that a combination of feedback on individual users’ power consumption and small financial incentives resulted in an average 16% group energy saving [54]. Furthermore, Sissa explores how raising awareness of the environmental sustainability of ICT through social and technological interventions can change user behaviour in ways that help to avoid rebound effects [55]. Sissa puts forward three types of interventions: creating *motivating social environments* involving providing real-time information about resource consumption, encouraging *psychological ownership* of environmental impacts, and the promotion of sustainable behaviour through *social proof*.

In an exploratory study, Suski et al. integrate an LCA of video streaming with a user survey [56]. According to their calculations, their non-representative sample (a convenience sample from the authors’ personal networks – skewing younger and more highly educated) were using 6.5% of an average annual personal carbon budget consistent with 1.5 degrees on video streaming. The results indicate that the global warming potential (GWP) intensity of video streaming is highly dependent on the choice of device, with smartphones having around a tenth of the impact of smart TVs. As such, the resolution and size of the screen are crucial factors for the GWP of video streaming. Interestingly, especially given the well-informed convenience sample, only 15% of respondents reported changing the default video resolution settings on their platforms or devices, suggesting that default settings have an important influence on the impact of video streaming.

In a particularly relevant paper, Pihkola et al. 2018 consider the importance of user behaviour and indirect effects when assessing the energy consumption of mobile networks [57]. They find that between 2010-2017 the energy efficiency of Finland’s mobile networks increased dramatically (from 12.34 kWh/GB in 2010 to 0.3 kWh/GB in 2017). However, they nonetheless estimate the electricity consumption of the network in 2017 to be roughly 10% higher than 2010. As such, energy efficiency improvements have not resulted in net energy savings due to rapid increases in the use of mobile devices and data and video content downloads [57]. As such, they argue that:

> "[I]n order to keep ICT-related energy consumption on a moderate level despite the rapidly increasing data usage and increasing number of devices per consumer, it is not enough to focus on technological development nor on developing more energy-efficient end-user devices, although both are important. We should also start informing consumers about the environmental impacts related to use of ICT and mobile technologies" [57].

In particular, they point to a lack of options for device repair and the fast pace of technological development and device obsolescence as leading to an unsustainably high turnover of user devices. They also suggest that unlimited data packages encourage unsustainable downloading practices, often without the consumer being aware of this [57].

Schien et al. assess the energy use of the delivery and consumption of online digital news content [58]. In particular, they analyse the impact of variability in content type (video or text), end-user device (desktop, laptop, tablet, smartphone), access network (mobile or WiFi), geographical location and browsing behaviour (the speed of changing between webpages) on the energy use of 10 minutes of content browsing on a news media website. They find that for text content, 10 minutes of browsing on a smartphone connected to the internet through 3G consumes the least energy of any combination of device and access network. In general, for text content, the power consumption of the device dominates, so larger, more power-hungry devices lead to high energy consumption (i.e. laptops and desktops). In contrast, for video content, the 3G access network is especially energy-intensive, so accessing video content over 3G on a smartphone, tablet or especially a laptop (due to higher device power) consumes the most energy (whilst accessing the same content over WiFi on a smartphone or tablet consumes least energy).

Some obvious and important lessons emerge from this work. Consuming video content on a smartphone over mobile data (specifically 3G in this case) is highly energy-intensive, but this consumption can be greatly reduced (by around 75-80%) by simply switching to a WiFi connection. Schien et al. therefore suggest that service providers could reduce the resolution of video content automatically when delivered over mobile data. We can also imagine an automatic prompt encouraging the user to switch from mobile data to WiFi if available. A key follow-up question is: when users have a choice between mobile and WiFi internet (i.e. when at home in a country like the UK), what proportion of users make sure they're connected via WiFi? Another important question is: in a scenario in which unlimited data contracts become the norm, what proportion of users are still likely to bother to ensure they're connected via WiFi? In other words, how does removing the economic incentive to be frugal with mobile data (due to cost penalties for exceeding one's limited allowance) affect the user's behaviour in switching from mobile data to WiFi when the latter is available?

Yan et al. remind us that changes in user behaviour can have impacts on energy use that are unexpected and largely unknown by users themselves. They assess the energy use of instant messaging (IM) applications compared with more conventional mobile services (SMS and MMS messaging and voice) [59]. They find that a message sent through WeChat (effectively China's version of WhatsApp) consumes more energy (0.13 joules vs. 0.09 joules). The reason for this is the 'hint message' function in WeChat (and indeed WhatsApp) which shows the recipient(s) that the sender is typing a message. On the other hand, they find that sending a picture via WeChat consumes less energy than a conventional multimedia message (MMS), as does sending a voice message through WeChat when compared to a conventional voice call (although they don't compare a conventional voice call with a IM voice call, an arguably more comparable functionality that certainly exists with WhatsApp). Whilst the figures for a single text-based message are tiny, with hundreds of millions of users shifting from SMS to IM and using IM regularly over long timescales, such a 45% increase in energy consumption would be highly significant. Furthermore, it is worth highlighting that certain features of IM (no limits, group interactivity, lots of very short messages in 'real-time' interactive bursts, ease of multimedia messages and linking to content on the web, etc.) are likely to lead to users sending and receiving many more messages than they did through SMS (this is certainly true in the lead author's case!).

There has been insufficient 'user-centric' work focusing on the relationship between 5G energy use and user behaviour. This includes questions about how and under what conditions 5G might change user behaviour to be more or less energy intensive (i.e. including encouraging or discouraging direct rebound effects); and the kinds of strategies that might be pursued by app designers, mobile operators and governments aimed at reducing energy intensive behaviours. A particular area of concern here is that flat pricing structures, declining per-bit data prices and the proliferation of unlimited data subscriptions will encourage wasteful practices and generate direct rebound effects.

Direct rebound effects are in fact implicitly accounted for in much of the literature considered in section 4.1.1, though they are not conceptualised as rebound effects as conventionally conceived. For instance, the EARTH project's assumption of a 1,000-fold increase in traffic between 2007-2020 could in a sense be seen as an implicit acknowledgement that making data less expensive on a per-bit basis will lead to an increase in the use of mobile data services. Interestingly, STL partners assume that traffic demand increases remain constant across the various 5G roll out scenarios they consider. In other words, the forecasted increases in traffic volume are the same in each country irrespective of whether and how quickly 5G is rolled out (i.e. 5G doesn't lead to more demand).

In the 5G literature considered here, this increased demand is implicitly conceptualised as an emerging phenomenon which exists independently of the technological and efficiency improvements which make it possible or likely. But what causes the projected traffic demand? Is it created by efficiency advances in the form of 5G or does it exist independently from such advances whilst making them necessary in response to ensure mobile networks remain sustainable in spite of its inevitable emergence? If data was to remain at current price levels per-bit in spite of 5G efficiency improvements what would happen to demand? We would argue that the idea this demand exists independently of 5G technology is at least questionable.

For example, industry surveys demonstrate that in certain regions (e.g. Western Europe) consumers are currently sceptical about the need for 5G and are actually satisfied with the data services offered by 4G networks [60]. Consideration is also given to the need to demonstrate the benefits of 5G to vertical industries [61]. In both cases the impression is not of *a priori* demand for 5G enabled functionalities existing independently, but of the need for the industry and other aligned actors to stimulate such demand. Moreover, according to Cisco, where mobile data is concerned, "[a]necdotal evidence supports the idea that overall use increases when speed increases" [62].

These anticipated demand increases are not, however, rebound effects in the traditional sense because 5G driven efficiency improvements are intentionally aimed at sustainably catering for the increased demand for data services they themselves arguably cause. These rebound effects are in other words the planned aim of the roll-out of 5G, not a surprising side-effect. We propose to call these effects *intended* rebound effects. This term refers to the situation in which the energy efficiency of services are increased with the aim of rendering their increased use more sustainable.

Such intended rebound effects and the increased demand they seek to enable are more sustainable in comparison to a scenario in which no energy efficiency improvements are made but the increased use of the service occurs, nonetheless. This, however, is arguably an unlikely scenario. They are, on the other hand, not necessarily more sustainable than either a scenario in which the efficiency improvements never occurred but nor did the increase in usage, or a scenario in which the efficiency improvements did occur but they were accompanied by strategies aimed at preventing a stepwise increase in usage (e.g. encouraging more sustainable user behaviour and limiting growth in traffic).

4.2.2 The enablement effect

The enablement effect refers to ICT-enabled energy savings in other sectors [63]. If rebound effects are negative indirect impacts that counteract to some extent the energy saving potential of energy efficiency improvements, then enablement effects are positive indirect impacts that counteract the direct energy consumption of ICT by inducing energy savings in other sectors of the economy. This may occur through the optimisation of processes and systems through the use of ICT (e.g. using sensors and data analytics to improve the efficiency of a manufacturing process); substituting physical products and resource-intensive activities with ICT services (e.g. e-books, online banking avoiding the need to travel to a branch); or measuring the resource use of consumption practices, informing users and encouraging behaviour changes (e.g. smart meters).

For instance, in 2008 the WWF estimated that by 2030 ICT could reduce CO2 emissions by 4,620 Mt CO2 [64]. The main contributors to these potential savings were smart vehicles and intelligent transport (1,486 Mt), e-commerce and dematerialization (927), the optimization of industrial processes (815), and smart buildings (545 from ICT in legacy buildings, and 439 from ICT for planning and operating new buildings). Smaller contributions were predicted to come from transport mode switching enabled by smart urban planning (190), telecommuting and virtual meetings (159) and ICT in energy supply systems (59). Whilst this study claims to be the first attempt to systematically map the potential enablement effects of a range of ICTs at a global level, it only assesses the potential enablement effects of ICT and does not produce estimates for the direct and rebound effects of ICT.

Erdmann and Hilty model the impact of ICT on GHG emissions in the EU in 2020 [49]. In particular, they assess the impacts of 11 application domains across the energy, transport, production and waste sectors. They take rebound effects (‘third order effects’ as they call them) into account as well as direct effects (‘first order effects’) and enablement effects (‘second order effects’). In terms of direct effects, it should be noted that Erdmann and Hilty include energy use associated with the use and disposal of ICT but not its production.

They model three scenarios with varying relevant non-ICT dynamics out to 2020 (i.e. energy prices, government regulation). The three scenarios saw a) strong economic growth and employment with weak regulation (’technocracy’), b) strong regulation with only moderate growth and stagnant employment (‘government first’) and c) steady economic growth (‘stakeholder democracy’). These scenarios reflect what Erdmann and Hilty term ‘political uncertainty’; whereas data uncertainty is reflecting in a worst-, mean- and best-case for each of these scenarios. For each case, Erdmann and Hilty calculate the level of GHG emissions in the EU in 2020 both with the level of ICT development expected for each case and with the level of ICT ‘frozen’ at 2000 levels (but other non-ICT variations between the scenarios and cases continue). The difference between the two figures represents the net effect of ICT developments between 2000-2020 on GHG emissions.

Looking at the mean cases across the three scenarios, we see that scenario B achieves the lowest level of emissions for 2020 but primarily for non-ICT reasons. Here ICT achieves a modest further reduction on already low emissions (from 89% of the level of emissions in the year 2000 to 86%).

Scenario A see emissions fall from 123% of 2000 levels to 115%, with scenario C seeing a drop from 123% to 113%. The only case in which ICT leads to a rise in emissions is the worst-case of scenario B (from 98% to 100%). In all other cases therefore, Erdmann and Hilty find that the enablement effect of GHG emissions savings in other sectors exceeds the emissions from direct and rebound effects. The most striking thing about these findings, though, is perhaps that the broader political and economic context is as if not more important in determining emissions levels than technological advances in ICTs.

Another assessment of the enablement effect of ICT came from GeSI (a strategic partnership of the ICT sector and other stakeholders) in 2015. They estimated that ICT could enable emissions reductions of 12.1Gt CO2e by 2030, a 20% reduction in emissions against the IPCC's (2014) 'business as usual' scenario [1][4]. These savings are expected to be split across 5 sectors: energy (1.8Gt CO2e), buildings (2), agriculture (2), manufacturing (2.7) and mobility (3.6). They also estimate that ICT will emit 1.25Gt CO2e by 2030, or 1.97% of global emissions, which represents a fall from their 2012 estimate for 2020 (1.27Gt CO2e, 2.3% of global emissions) [5]. The enablement effect is therefore estimated to lead to the avoidance of almost 10 times the emissions emitted by the ICT industry by 2030. When estimating the emissions of the ICT industry itself, the report states that, where possible, scope 1, 2 and 3 emissions were taken into account; and the estimate includes the emissions resulting from user devices, networks and data centres. This energy saving potential primarily arises from ICT's ability to connect people and machines, monitor and track social and natural processes, analyse and optimise the efficiency of energy and material use, and automate processes across a range of sectors [65]. Whilst the headline 12.1 Gt CO2e enablement effect finding does not include any rebound effects, the authors do calculate a total potential rebound effect of 1.37Gt.

Looking more specifically at mobile networks, a 2019 report from the mobile operators industry group GSMA and the Carbon Trust estimated that in 2018 the enablement effect from mobile communications technologies avoided the emission of 2,135Mt CO2e (GSMA and Carbon Trust 2019). These emissions reductions occur largely due to IoT applications (e.g. smart homes, grids,

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[4] The 20% reduction in emissions compared to the IPCC 'business as usual' figure avoids the double counting of ICT-enabled abatement potential in the energy sector already considered in the baseline scenario. The 12Gt CO2e figure includes this potential. Removing the abatement potential from the energy sector (1.8Gt CO2e) results in a remaining non-energy sector enablement effect of 10.3Gt CO2e.

manufacturing and transport) and behaviour changes due to smartphone use (e.g. reduced travel for work and leisure, reduced travel associated with mobile banking and shopping, accommodation sharing, and increased use of public transport due to real-time updates) (see Fig. 2). Finally, the report suggests that by 2025 this enablement effect could double due to projected increases in smartphone users and IoT connections [63].

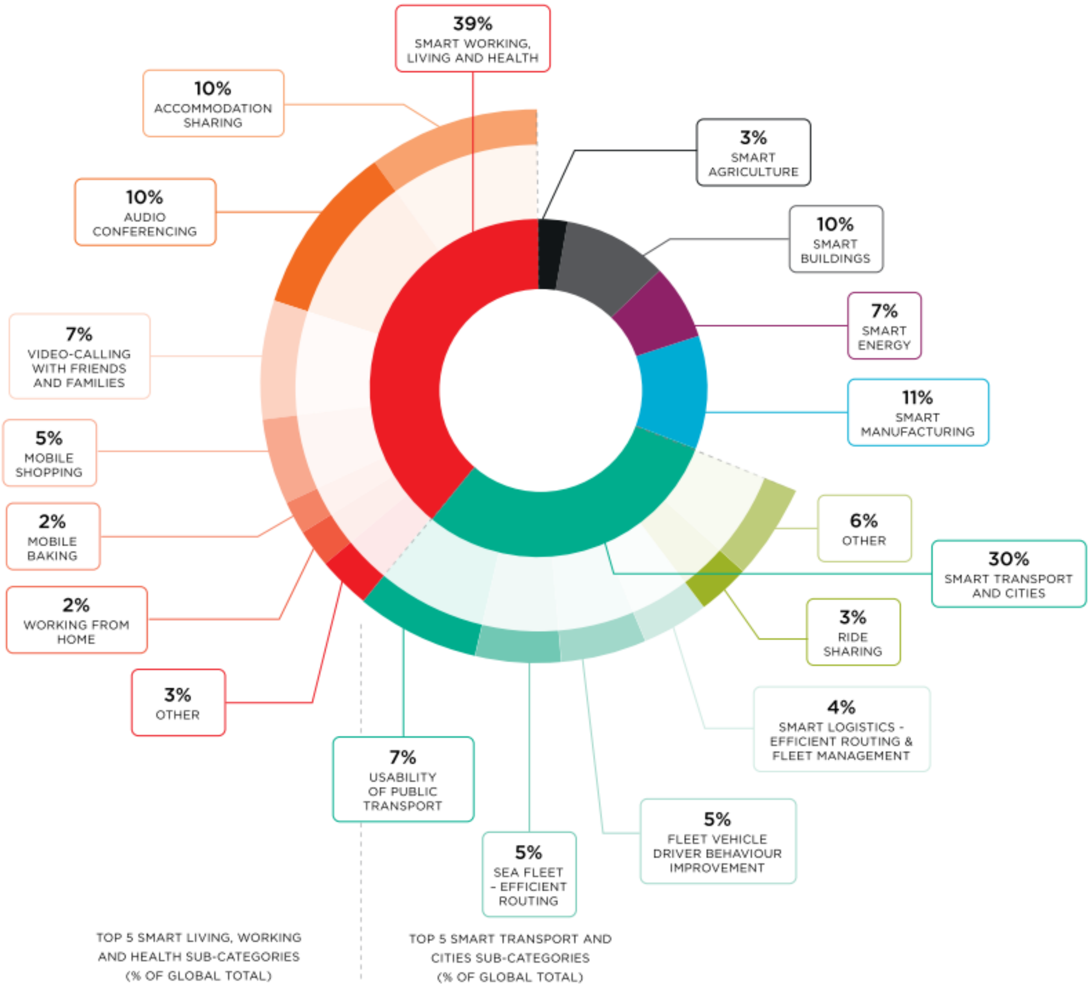

Fig. 2: Avoided carbon emissions enabled by mobile communications by category in 2018 [63]. ©GSMA. Used with permission.

The same report estimates the mobile sector’s emissions to be 220Mt CO2e (or 0.4% of global emissions), meaning that the emissions avoided by mobile communications technologies are about 10 times greater than the footprint of the industry itself. The figure for the mobile sector’s emissions includes operational and embodied emissions for networks (included network operators internal data centres), smartphones and mobile phones. The estimate of the enablement effect does not generally include rebound effects, although they are included in two use cases where they are said to be clearly identifiable (additional energy requirements associated with working from home, e.g. heating; the emissions of ride-hailing vehicles). Furthermore, whilst the authors assess only the direct impacts of mobile networks and user devices, they allocate all of the energy saving potential to mobile communications, even for activities that require other technologies to function (e.g. video-conferencing requires video equipment and cloud-based servers).

Finally, a report by Analysys Mason and Huawei argues that 5G in combination with AI, IoT and cloud computing can significantly reduce the GHG emissions of the energy, healthcare, and manufacturing sectors by enabling new ways of operating that would be impossible or unaffordable without 5G [66]. Rather than producing an overall estimate of the enablement effect of 5G (and associated ICT technologies), this report instead conducts a series of LCAs and parameter comparisons on quite specific use cases within these sectors (unmanned aerial vehicles used for gas pipeline inspections reducing GHG emissions by 39%, remote CT consultations reducing emissions by 99%, and AI cameras for manufacturing inspection reducing per-unit energy consumption by 94%).

5. Discussion

In this penultimate section, we focus on policy implications and recommendations, as well as the need for more carful considerations of ICT convergence.

5.1 Whole network assessments, embodied energy, rebound effects and user behaviour, and enablement effects: implications and recommendations

We identified just four studies that assessed the energy use implications of 5G (and beyond 4G) mobile network technologies from a whole network perspective. Across these studies a range of hardware improvements, energy efficient radio resource management techniques and network deployment and management strategies are assessed. The studies use different baseline approaches: GreenTouch and Tombaz et al. compare hypothetical future networks equipped with their solutions against contemporary networks, whereas EARTH and STL partners assess the energy savings possible with their solutions (on an average-per-site or joule-per-bit basis) and model different technology adoption scenarios. The former, more static approach gives a sense of what is technically possible, but remains highly hypothetical because in reality new networks take time to roll-out and coexist with legacy networks during and after their roll-out.

The other key difference between the studies is the traffic increases they assume between the baseline and future scenario. Tombaz et al. assume a 4-fold increase in traffic from 2014 levels, GreenTouch assumes an 89-fold increase from 2010 levels, and EARTH assumes a 1000-fold increase from 2007 levels, whereas STL partners use a distinct projection for traffic growth for each country but do not disclose what these projections are. These and other differences in approach, metrics and data disclosure make direct comparisons difficult because it is not always clear how much traffic is being served by these modelled future networks over what size of network (by area or number of subscribers) with what energy efficiency.

Nonetheless, these studies taken together do begin to give a sense of what energy efficiency improvements might be technically feasible in future mobile networks, and the kinds of roll-out timescales over which they might be achieved. However, these studies focus on the operational energy use of radio access networks (and core networks in the case of STL partners), and so overlook potentially important issues that will help to determine the energy use implications of 5G and future mobile networks. These issues are the embodied energy use of mobile networks (especially from large-scale network equipment swap outs and mobile phone manufacturing), and indirect energy use effects.

Whilst STL partners acknowledge that they don’t consider the embodied energy associated with the manufacture and installation of 5G networks, they argue that this is justified because it is likely to be broadly comparable with the embodied energy associated with 4G and it is expected to be a small fraction (<5%) of the total energy use of 5G networks [26]. They do not provide a source for this <5%

figure. As we saw in section 4.1.2, embodied energy had previously been considered to represent a much larger fraction of the energy use of previous generations of RANs. For instance, based on data from Ericsson, Malmodin et al. assumed that embodied energy was responsible for 20% of the total carbon footprint of a 3G BS (assuming a lifespan of between 7-20 years and global average electricity mix) [39]. Furthermore, Humar et al. estimated that embodied energy accounted for 36% of the total energy consumption of a BS over a 10 year lifetime [33]. A recent report from the NGMN puts the figure at 10-15% of the use phase emissions (assuming a 10 year lifetime and global electricity mix) [67]. Due to their increasing sophistication and short life-spans, the issue of embodied energy becomes more significant if we take the manufacturing of smartphones into account. As we have already seen, in 2011 the EARTH project estimated that by 2020 mobile device manufacturing and RAN operation would account for a comparable share of the total carbon footprint of mobile communications (around 30% each) [21,31].

Clearly, given the pace of technical change in this area, these figures are likely to be out-of-date. As such, it is crucial that reliable and up-to-date figures for the embodied energy associated with 5G devices and infrastructure are available for decision-makers and are used to inform the careful consideration of the environmental impact of different equipment replacement cycles. Taking embodied energy into account may alter the particular technologies or strategies that are favourable from an energy saving perspective, and may even exceed the operational energy savings for strategies based on the installation of lots of new equipment. At the very least, decision-makers should be sceptical about the energy saving potential of strategies based on the large scale swap out of equipment that do not even mention let alone take account of the embodied energy associated with the required state-of-the-art equipment.

Given that a new generation of mobile network emerges every decade, large scale swap outs of infrastructure occurring every 10 years pose challenges from a sustainability perspective, as does the average 3 year lifespan of a smartphone [3]. Therefore, more focus should be placed on prolonging device lifespans, increasing the adaptability of infrastructure components, and enabling smartphone repairs. In the latter case, reports that some mobile phone manufacturers intentionally design their phones to prevent repair and encourage more frequent upgrading are obviously problematic [68]. In this context, the recent recommendations of the UK Parliament’s Environmental Audit Committee to enshrine the ‘right to repair’ smartphones and other electronic devices in law, to incentivise and publicise device repairability, and to ban ‘planned obsolescence’ should be given serious consideration [69].

A recent report from the NGMN demonstrates that the industry are starting to take the issue of the environmental and material footprints of network equipment increasingly seriously [67]. The report sets out principles and approaches aimed at the eco-design of hardware focusing on longevity, repairability, upgradeability, reusability and recyclability with a view to establishing a circular economy for the telco ecosystem. With regards to upgradeability, the report advocates for modular design approaches that enable components that require regular upgrades or capacity extension to be plugged-in to existing sites without the need for a full-scale BS swap-out. The report represents an excellent starting point in addressing the concerns about the embodied energy use of network infrastructure raised here, and we echo the authors’ call for stakeholders to participate in standardisation efforts on equipment environmental footprint reduction, especially as the industry begins to look toward 6G standardisation processes.

Whilst STL partners assume no changes in traffic growth based on wider and quicker adoption of 5G (i.e. they assume that 5G does not lead to increases in data traffic), other studies arguably do consider direct rebound effects in so far as the increases in traffic they assume are caused by improvements in energy efficiency associated with 5G leading to data being cheaper per-bit and so more widely used. However, the literature considered throughout this paper tends to view 5G (and its associated energy efficiency improvements) as a necessary intervention in order to render future traffic growth environmentally and economically sustainable. This future traffic growth is therefore implicitly framed as occurring independently of 5G and its associated energy efficiency improvements. We find this framing implausible, and consider it likely that 5G will itself be the cause of at least some of the traffic growth it is being promoted as a necessary solution to. We believe that the experience of previous generations of mobile networks demonstrates that when energy efficiency improvements lead to a reduction in the cost per-bit of data and when higher data availability and smartphone computational capabilities enable more data-intensive applications, then app developers and users tend to make the most of this abundance of computational and data availability by developing and adopting data-intensive applications and practices. For example, virtual reality is an oft-mentioned use case of 5G, and mobile gaming will no doubt become more sophisticated (and energy-intensive) with 5G. In other words, affordable unlimited data subscriptions will lead to high-consumption data practices and an increase in data traffic, representing a direct rebound effect that if left unchecked will counteract at least a portion of the energy savings associated with the technologies and strategies discussed in this paper. As Pihkola et al. demonstrate, dramatic improvements in the energy efficiency of mobile networks do not ensure that their total energy consumption will fall [57], and therefore strategies aimed at limiting demand rather than merely catering for and encouraging it may be required.

A greater understanding about how 5G will shape user behaviour, including how data pricing points and structures will affect the adoption of frugal or frivolous data use practices and the energy use implications of this, is sorely needed. This kind of knowledge needs to be more explicitly factored into data traffic growth estimates, so that they take into account the scope for direct rebound effects where this is warranted. As well as helping to identify the scope for direct rebound effects, more user-oriented approaches are required to devise strategies aimed at encouraging less energy-intensive user behaviour. An obvious starting point here would be to establish existing levels of awareness amongst users about the energy use implications of different user practices, with a view to encouraging greater user awareness and less energy-intensive user practices. The current widespread invisibility of the relative energy use impacts of different user practices is an obvious problem. For instance, how widespread is awareness that streaming video over 3G consumes more energy than using WiFi (see Shien et al. above), or that instant messaging consumes more energy per message than conventional SMS (see Yan et al. above). Increasing user awareness of the environmental impact of different user practices and seeking to encourage more frugal practices is clearly important, however the responsibility shouldn’t fall solely on users. Application developers should factor sustainability considerations into the earliest design stages. Discouraging hundreds of millions of users from switching to a new, less energy efficient application would not be necessary if app developers ensured that their apps were a more energy efficient way of delivering a particular service.

As has been argued with ICT in general, there are hopes that the enablement effects of 5G-enabled energy savings across various sectors will exceed its energy use from direct and rebound effects. On the basis of our review, there is currently insufficient evidence relating specifically to 5G to definitively support the view that enablement effects will ensure that 5G contributes to a net reduction in energy use. In general, in the absence of a global carbon constraint, Freitag et al. have cautioned against assuming that ICTs will enable emissions reductions in other sectors due to partial substitution (e.g. videoconferencing being used alongside in person meetings) and the potential for efficiency improvements to lead to rebounds [8]. They argue that “as yet there is no evidence in the multi-decade history of ICT-driven efficiency savings that enablement works for reducing overall emissions" [8]. In fact, they go as far to argue that "it is more likely that ICT enables emission increases in other sectors because it enables efficiencies" [8].

5.2 ICT convergence: the need for the careful consideration and integrated assessment of energy use implications

As with any assessment or review of the energy use of ICT, bounding the focus on this review was a key challenge. This is because of ICTs tendency toward technological convergence. Whilst we limited our focus to 5G and its implications for the energy use of future mobile networks, direct rebound effects and enablement effects in other sectors of the economy; 5G is closely associated with a number of other ICTs and there is great scope for further convergence that may have energy use implications and that will require careful consideration and further research. For instance, Analysys Mason and Huawei's report into the enablement effects of 5G considers the potential of 5G to reduce emissions in vertical industries in combination with cloud computing, artificial intelligence and the IoT [66]. Furthermore, generating and analysing large amounts of network data through big data and AI approaches is increasingly seen as an important strategy to further improve the energy efficiency of mobile networks (see, for example, [70–73]). Similarly, there are increasing expectations about the integration of 5G and blockchain technology predominantly focusing on privacy and security issues [74], which will likely have energy use implications that require careful consideration and further research focus . Much like 5G, these other emerging ICTs hold both opportunities and dangers for ICT energy use and GHG emissions, and have dedicated research communities committed to assessing their environmental impacts and seeking to shape them to become more sustainable.

For example, in relation to AI, according to Amodei and Hernandez, between 2012-2018 the amount of computational resources required to train state-of-art deep learning models increased by x300,000 (doubling every 3.4 months) [75]. Strubell et al. offer an assessment of the carbon footprint of training a number of common neural network models for natural language processing [76]. In one case study, a natural language processing model required 27 years of specialist computation to develop (i.e. 60 specialist computers running constantly for nearly 6 months), with an estimated carbon footprint of 35.5tCo2e [76]. Freitag et al. suggest that big data, data science and AI present both opportunities and threats for the carbon footprint of ICT in general. Whilst AI and data science could help to bring about a smart, low carbon future alongside IoT by helping to realise and optimise smart grids, cities, homes, logistics, agriculture and so on; they may also drive increases in data storage and processing and growth of data centres [8]. Finally, Schwartz et al. point out that the AI research community's focus on accuracy is leading to increasingly computationally intensive deep learning models. They advocate for a 'Green AI' approach that values efficiency alongside accuracy and performance, as opposed to an approach that values performance improvements at any economic and environmental cost [77].

Although beyond the scope of this study, further convergence of 5G and other digital technologies will have energy use implications which will require careful consideration and integrated assessment through further research.

6. Conclusion

The amount of research now being conducted into the energy efficiency of mobile networks is encouraging, and the innovation on display in this field and the energy efficiency improvements it makes technically feasible are impressive. However, we have identified a number of ongoing areas of insufficient research focus and publicly available evidence concerning the emerging energy use implications of 5G. First, there remains a paucity of publicly available, peer reviewed, fully transparent and up-to-date whole network assessments of the operational energy use of 5G networks. Second, the embodied energy associated with network equipment and user devices is neither accounted for nor targeted in much of this literature. Third, the positive (enablement effects) and negative (rebound effects) indirect energy use effects of 5G have not been adequately assessed, nor has sufficient attention been paid to how user behaviour might be shaped in order to avoid rebound effects. These issues strike us as crucial for not only understanding the energy use implications of 5G, but actively seeking to shape 5G and how it is used to ensure its energy saving potential is actually realised in practice.

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