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Evaluating the Energy Consumption of Mobile Data Transfer—From Technology Development to Consumer Behaviour and Life Cycle Thinking

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Abstract: Mobile data consumption in Finland is among the highest in the world. The increase in mobile data usage has been rapid and continual future growth is foreseen. Simultaneously, consumer behaviour is changing. While new end-user devices are more and more energy-efficient and energy consumption per transferred gigabyte has significantly decreased, people spend more time and consume more data via their mobile devices than ever before. Does the increased usage outweigh the energy savings that have been achieved? What options are available for tackling increasing energy demand? And should consumers have a role to play in this discussion? This paper examines the current and future trends that results from the energy consumption of mobile data transfer and mobile networks in Finland. The findings presented in this paper are based on a top-down energy intensity estimate and publicly available data, which was employed to construct an illustrative trend (kWh/gigabyte) for the energy consumption of transmitted mobile data for the years 2010–2017. In addition, energy consumption related to mobile data transfer is discussed from a life cycle perspective, considering both direct and indirect energy use. Finally, the challenges in conducting such assessments are examined.

Keywords: energy consumption; mobile access networks; consumer behaviour; life cycle thinking

1. Introduction

Information and communication technology (ICT) is increasingly becoming an integrated element of people's daily activities. Developments related to the Internet of Things (IoT) and digitalisation has increased the use of ICT almost everywhere. The number of mobile devices in use, such as smart phones, is growing globally, leading to an increasing demand for mobile data [1]. Fulfilling the demand for mobile data and new services, such as high-resolution videos and virtual and augmented reality, is expected to increase the amount of energy consumed by mobile networks (See e.g., Reference [2,3]).

In 2016, advanced mobile networks (LTE) reached almost half of the world population. In the least developed countries, mobile access was on average significantly cheaper than fixed broadband access [4]. According to the International Telecommunication Union (ITU) (ITU is the United Nations specialized agency for information and communication technologies), access to ICT and broadband has the potential to serve as a major accelerator for reaching the UN2030 Goals for Sustainable Development [5]. While mobile broadband connections hold great potential for positive sustainability impacts, estimated increase in the energy consumed by mobile networks requires attention.

The aim of the paper is to discuss the important role that mobile access networks play within evaluations of environmental impacts and the sustainability of the Internet and electronic services. Additionally, the paper presents a trend-estimate of the electricity intensity of mobile access networks in Finland. The growth of mobile data usage in Finland has been rapid and continual ongoing growth is foreseen. In 2016, the average monthly use of mobile data per Finnish inhabitant was 16 gigabytes and mobile data transmission volume exceeded 1 million terabytes [6]. During 2017, the average mobile data consumption per Finnish inhabitant reached 24 gigabytes per month [6] and Finns are currently the top users of mobile data in the world [7]. In 2017, data consumption in other Nordic and Baltic countries ranged from between 4 and 9 gigabytes per month per capita [8]. Therefore, although preliminary, results from Finland could be of interest to other countries, since similar developments related to data usage patterns might be expected in other countries in the near future. The number of mobile broadband subscriptions has increased rapidly and in December 2016, there was (statistically) nearly one high-speed mobile broadband subscription for every inhabitant living in OECD countries [7]. In Finland, the average amount of mobile subscriptions per inhabitant was more than 1.7 [8].

Life cycle assessment (LCA) studies are important for evaluating the environmental impact of ICT related services. While several studies have assessed the environmental impacts of ICT and data transfer, to the best of our knowledge, there is a lack of information about the environmental impacts of mobile services and networks. Existing studies (such as [9–12]) provide important information and a good starting point. However, due to rapid technical developments and changes in user behaviour, existing studies become quickly outdated. For example, the current situation in Finland is very different than it was in the past studies, due to the wide population coverage of the 4G LTE network and high mobile data consumption figures.

Within this paper, our preliminary estimates of the energy intensity of mobile access networks are compared with existing estimates of the energy intensity of data transfer (considering mobile and fixed access networks and ICT sector as a whole), in order to identify potential development trends and patterns. In addition, our findings are compared with current literature in the field. This paper focuses on two aspects that were identified as being of significance in attempts to tackle the increasing overall energy demand related to mobile data transfer: radio network technology development and user behaviour (An earlier version of the paper with data from years 2010–2016 has been published in the Proceedings of the 5th International Conference on ICT4S, Toronto, Canada, 14–18 May 2018).

2. Materials and Methods

An empirical part of the study consists of an estimation of the overall energy consumption of the Finnish mobile network operators during the years 2010–2017. During this period, mobile data consumption in Finland started to grow exponentially. As part of the study, a kWh/transferred gigabyte trend was constructed, using a top-down approach and basic statistical analysis methods. In a top-down approach, the estimated network level total electricity consumption is divided by total data that has been transferred through the network [13]. Applied data was collected from publicly available data sources. In Finland, the total mobile data transmission volume is reported semi-annually by FICORA (Finnish Communications Regulatory Agency). In the current study, the total energy consumption of mobile network operators was estimated based on data that was collected from the published annual reports and sustainability reports of the three biggest operators in Finland, published between years 2010–2018. Together, these operators covered 99% market share of mobile subscriptions in Finland during 2017 [14].

The biggest mobile operator in Finland has disclosed how the majority of its climate impact results from energy use and that the energy consumption of data communications networks account for approximately 80 per cent of its carbon footprint [15]. According to [16], approximately 57% of the power consumption of a typical wireless cellular network could be allocated to base stations. Applying these rough estimates in combination with publicly available energy consumption data from corporate reports, an illustrative trend (kWh/gigabyte) for transmitted mobile data was constructed for the years 2010–2017. The factors that were assessed were somewhat uncertain and dynamic. However, the assessment was conducted to construct a relative annual trend. The aim of this study was also to understand the magnitude of telecommunications-related electricity consumption in comparison to overall electricity consumption in Finland and to ascertain how the electricity consumption related to networks has developed during recent years, taking into account the rapid growth in data consumption and the recent investments in 4G LTE network technology. The results of the empirical analysis are presented in Section 3, together with an evaluation of the technological aspects that are relevant for the energy consumption and energy efficiency of mobile networks.

The empirical part of this research was complemented with a traditional literature review [17], in which the available literature describing life cycle environmental impacts related to ICT and electronic services was reviewed, focusing on LCA studies relevant for mobile data transfer and mobile access networks. The aim of the literature review was to follow the principles of life cycle thinking and to acquire an understanding of the potential impacts that mobile networks have on the overall energy consumption related to the life cycle of mobile services. In addition, the aim was to understand the role of consumers and end-users of the mobile services, as previous research has indicated that the biggest environmental impact is often related to the use phase of ICT and related devices and services (See, for e.g., Reference [10]). An evaluation of the findings of the scientific literature was complemented with relevant information collected from technical reports, policy documents and standards.

The findings of the literature review indicated that many of the existing life cycle studies have focused on fixed access networks, while fewer studies have considered the environmental impacts of mobile access networks. In addition, while a lot research on the energy efficiency of mobile networks has been published and significant technical development is ongoing (see Section 3.2), it seems that studies with a life cycle view are much rarer in this context. Taking into account the growing importance of mobile networks and data transfer in our societies, we consider this to present an emerging topic that requires more attention in the future. Thus, this paper aims to take a first step in addressing this gap, pointing out the need to also focus on consumer behaviour when addressing energy consumption related to electronic services and ICT in general. The findings of the literature review are discussed in Section 4.

3. Results

3.1. Estimation of Mobile Operators' Energy Consumption and Energy Intensity of Data Transfer in Finland

The development of the total energy consumption of the main mobile network operators in Finland between 2010 and 2017 are presented in Figure 1. An estimate of the overall energy consumption of all operators in Finland was around 0.6 TWh/a in 2017. This corresponds to 0.7% of the total annual electricity consumption in Finland in 2017 (85.5 TWh/a). Rapidly increasing mobile data consumption has placed pressures to mobile operators, nonetheless, it seems that these pressures have not yet led to a corresponding growth in total energy consumption related to mobile networks. However, as it is anticipated that the growth in data usage will continue (see Figure 2), this is a topic that requires attention in future.

The constructed growth trend for the transmitted mobile data in Finland is presented in Figure 2. The growth trend was prepared based on the data published by FICORA in 2017 [6]. The polynomial and exponential trends (y = y(x)) presented in Figure 2 were estimated by means of least squares fit using the data in the histogram. X in these equations refers to numbers from 1 to 11 corresponding to the years 2010 through to 2020. The statistic R^2 (R-squared, i.e., coefficient of determination) describes goodness of the fit. Values close to one refer to a good fit between the estimated equations and the historical data.

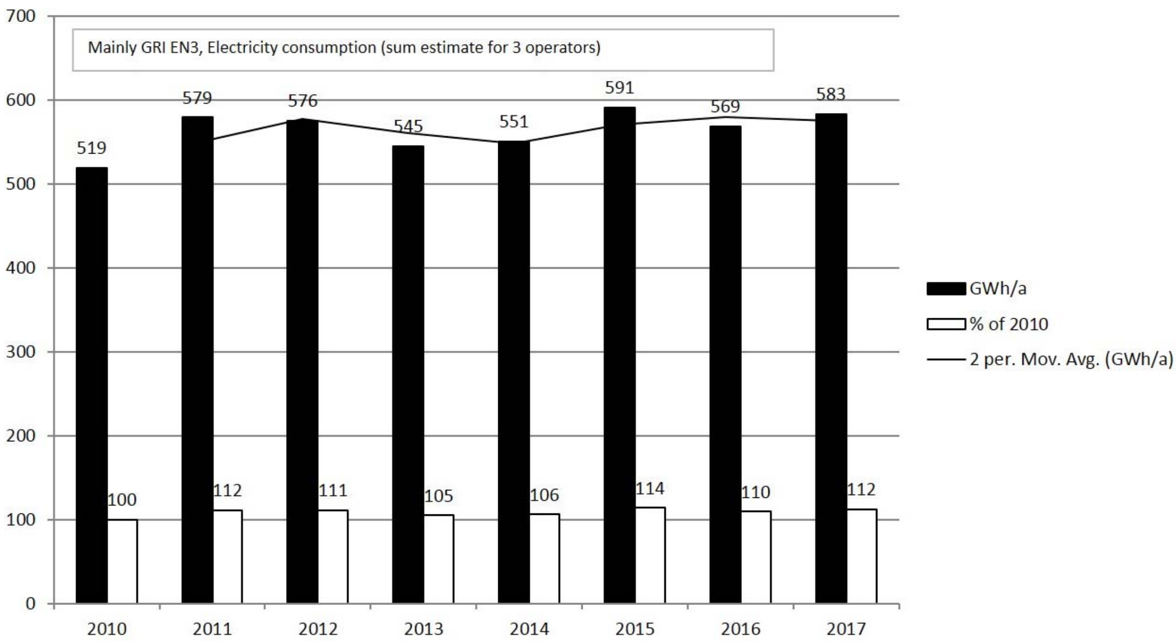

Figure 1. Total annual electricity consumption estimates for the three main operators' activities in Finland. This estimate was compiled based on various company reports. The main data sources included the total energy consumption figures (reported according to GRI EN3 as part of corporate environmental reports). Some uncertainty is related to the various system boundaries applied by different organisations in their reporting. (Mov. Avg. = Moving average calculated over a two-year period. If 2010 is set to 100%, current consumption level would be roughly 10% higher).

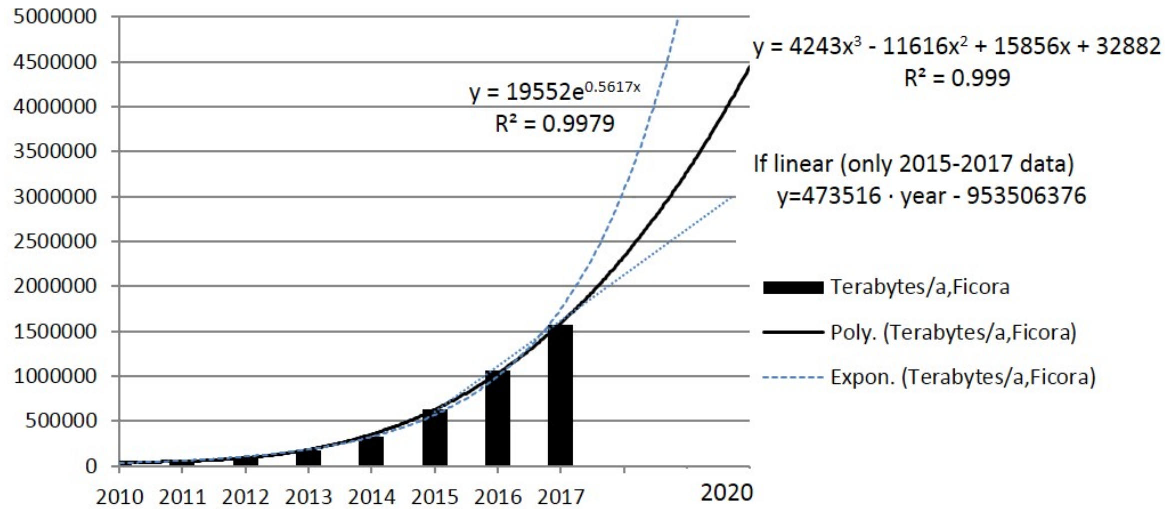

Figure 2. Growth of the transmitted mobile data in Finland during 2010–2017 in terabytes and corresponding statistical trends and estimates until 2020. The volume contains both the traffic the user has sent (uploaded) and the traffic the user has received (downloaded). Vertical Y-axis show terabytes per year and horizontal X-axis is the corresponding year. Data source for mobile data transmission volumes: FICORA 2017.

During the second half of the last reported year (2017), the growth in data transmission volumes was 40%, in comparison to the consumption figures from the previous year and the total amount of transferred data in 2017 reached 1,500,000 terabytes [6]. After a period of fast exponential growth, the pace of growth slowed down, from an exponential equation to a polynomial trend estimated by a means equation. However, the growth rate remained significant. If the polynomial growth trend continues, data consumption could reach 4.5 million terabytes per year by 2020. In addition to exponential and polynomial trends, a linear trend line based on 2015–2017 data was constructed as a lower estimate for 2020. Even if future growth is linear, the current levels of data consumption double by 2020. In this context, it is important to note that previous consumption levels do not predict future consumption, as any change could affect future development. Instead, these developments indicate potential future developments in the event the pace of growth follows earlier development trends.

During the assessed period, the total number of mobile subscriptions in Finland remained rather stable, being 9.5 million in 2017. According to the statistics provided by FICORA, the majority (two-thirds) of the subscriptions were mobile subscriptions (including voice and data), while one fifth were mobile broadband subscriptions (including only data) and 10% were voice-only subscriptions (no data transmission included). In Finland, the number of mobile subscriptions per capita was more than 1.7, in comparison to 1.2–1.6 in other Nordic and Baltic countries, whereas the growth rate in the number of fixed broadband subscriptions was lower in comparison to other countries in the region [8]. According to OECD statistics, the average monthly mobile data consumption per mobile broadband subscription in Finland in 2016 was the highest in the world (11 GB/month/subscription) and the second highest mobile data consumption level was in Latvia (8.2 GB/month/subscription) [7].

By combining the overall electricity consumption estimate for production networks (80% of operators' overall consumption) (Figure 1) with previous estimates of overall data usage (Figure 2), an indicative trend of electricity consumption (kWh) per transferred gigabyte for the years 2010–2017 was created (Figure 3), together with an estimate for the coming years. The results presented in Figure 3 indicate that the specific electricity consumption per transmitted gigabyte has decreased substantially.

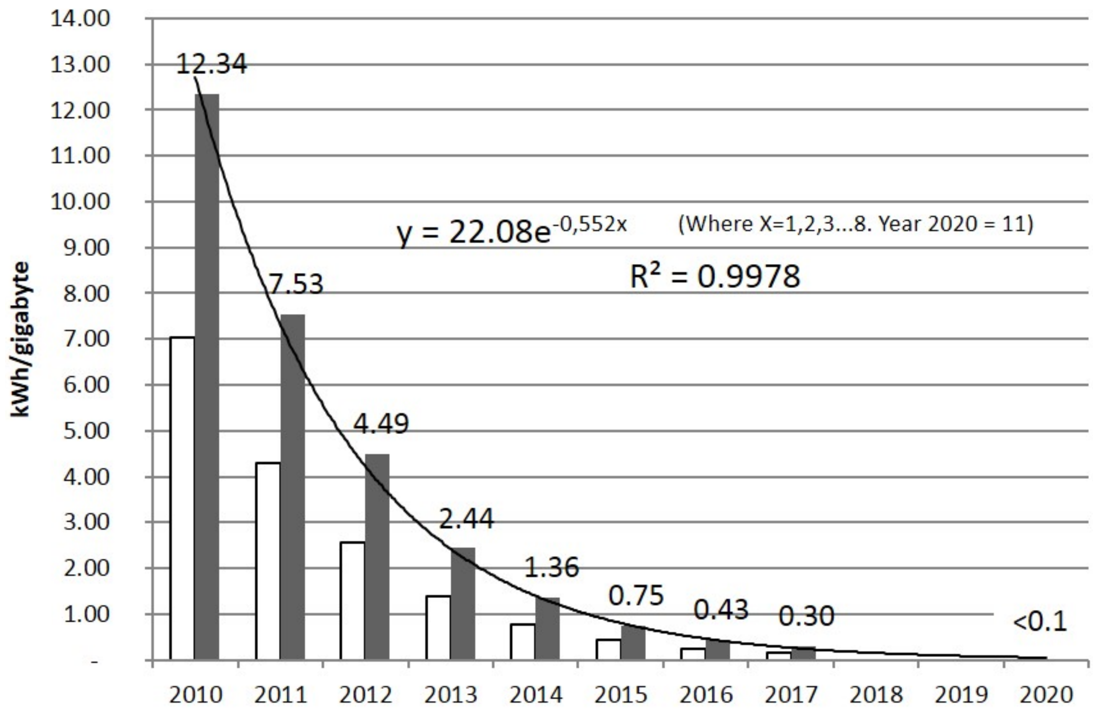

Figure 3. Development of energy efficiency of transmitted mobile data (kWh/gigabyte) in Finland during 2010–2017. Grey bars represent estimated consumption for production networks and white bars for base stations only. Exponential trends (y = y(x)) until 2020 were estimated by means of least squares fit using the data in the grey histogram. X in these equations refers to numbers 1 to 8; and 11 corresponding to years from 2010 through to 2017; and 2020.

Based on data usage and electricity consumption data, it can be estimated that, during 2016 the specific electricity consumption per one gigabyte decreased below the level 0.5 kWh/gigabyte and will continue to decrease when the capacity utilisation factor of existing 4G LTE networks improves. Based on the equation (presented in Figure 3) the 0.1 kWh/gigabyte level could be achievable by around 2020 even though annual electricity consumption might increase in comparison to the current level. Thus, new efficiency improvement measures should be introduced and implemented to restrict and control increasing operational costs of electricity.

The results presented here can be considered as preliminary and a direct comparison with other available studies is not possible. However, a brief analysis of the available literature is included in order to evaluate the accuracy of our results. It is difficult to compare our findings to those of earlier studies because the rather rapid technical development and increase in data consumption entails that available estimates quickly become outdated. In addition, life cycle analyses that include energy consumption figures are often case-specific and largely dependent on the assumed network technologies, end-user devices and assumptions related to the use phase.

In previous studies, several estimates about the electricity intensity of Internet data transmission have been presented and thoroughly analysed (See: [18]). Electricity intensity in this context has most often been defined as energy consumed per amount of transmitted data [19] and is commonly expressed as a ratio of kilowatt hours per gigabyte (kWh/GB). While existing studies typically use different approaches and system boundaries, most of the existing estimates consider only fixed-line access networks and less information about the mobile access networks seems to be available. This is most likely due to the previously dominating role of fixed access networks in several countries. However, the latest developments related to increasing mobile data usage and wider coverage of advanced mobile network technologies (LTE, 4G) indicate that more information about the environmental impacts related to mobile networks and mobile data transfer will be needed in the future.

Using data volumes from the year 2010 Malmodin and colleagues estimated electricity consumption per data volume as follows: 0.08 kWh/gigabyte for averaged fixed broadband access network, compared to 2.9 kWh/gigabyte for average 3G mobile broadband access network and 37 kWh/gigabyte for average 2G mobile communication [10]. Within the same study, the energy consumption of data transmission and IP core network was estimated to be 0.08 kWh/gigabyte. Different from our study, the estimates presented by [10] were prepared using a bottom-up approach, in which the starting point was the measured energy consumption of dedicated network devices.

A modelling and scenario study by Andrae and Edler [3] included estimates of the electricity consumption of fixed and wired access networks together with estimates of global ICT related energy consumption for the years 2010, 2020 and 2030. Their analysis of the electricity consumption of fixed and wired access networks and data centres revealed that wireless access networks (WAN) are currently considered more energy consuming per kWh/GB than fixed access networks [3].

However, due to the increasing data use and improved efficiency of radio network technologies, the situation should change by the year 2030, when 5G network technologies are predicted to become dominant. To achieve this goal and to keep the total electricity consumption of mobile data networks at a reasonable level, an energy efficiency improvement of more than 99 percent per kWh/GB for the WAN is required [3]. The energy consumption estimates presented in [3] are relatively close to those generated in our study. In the current study, it was estimated that the specific energy consumption of mobile data transfer in Finland could be under the level of 0.1 kWh/GB by 2020. This is in line with the estimated global consumption levels between 0.047–1.04 kWh/GB by 2020 presented in [3]. Similarly, our estimate of energy consumption (kWh/GB) in 2010 was 12.3, which is within the range estimated by Andrae and Edler within their study (6–15 kWh/GB) [3].

3.2. Energy Efficiency Related Developments in Mobile Networks

Energy efficiency in wireless communications is usually defined as the number of successfully received bits divided by the energy consumed for transmitting and receiving those bits. An alternative definition is the throughput divided by the consumed power, which also results in the same bit/J quantity. (Note that these definitions are different from those used in the previous section, where the focus was more on consumed energy than transmitted bits). For the earlier mobile access generations until 4G, there have not been any requirements for energy efficiency. However, the energy efficiency has been continually improving mostly due to the considerable cell throughput improvements. This behaviour is also visible at national level in Finland, as seen in Figure 3.

More recently for 5G systems, network energy efficiency has been defined as one of the main requirements targeting 100-fold improvement over the 4G systems [20]. The same requirements also stipulate that the area traffic capacity (bit/s/m^2) should improve by a factor of 100. From these requirements, it can be concluded that the power consumption of the 5G network should remain at the same level as the current 4G network power consumption. Very roughly speaking, if the traffic volume in 5G networks increases to more than 100-times that of the traffic volume in 4G networks, it is reasonable to expect that the power consumption in the future mobile access networks will increase.

Increasing mobile data usage might lead to a growing total energy consumption within the mobile access networks in the near future. The background for this is that traffic volume is currently increasing at a rapid rate [6] driven by the flat rate pricing strategy of the Finnish operators. Currently, there are three operational mobile access network generations: 2G/GSM, 3G/UMTS and 4G/LTE. As the 4G coverage is almost nationwide and the penetration of 4G smart phones and mobile routers is increasing, the traffic volume is shifting from 3G to 4G networks. This has forced the operators to add more capacity and install more 4G equipment to fulfil the data rate expectations of their customers, which, in turn, increases the energy consumption. On the other hand, even though the traffic volumes of the legacy 2G and 3G networks are decreasing, they still consume a significant amount of power. For example, according to the EU Code of Conduct for network equipment, 2G and 3G base stations consume approx. 70% of the busy hour power when they are at the low-load state [21]. Finnish operators have not yet published any schedules for closing down their 2G and 3G networks, which would obviously bring power consumption savings. Currently, the penetration of voice-over-LTE (VoLTE) service over 4G networks is low, which keeps the 2G or 3G coverage mandatory in order to make conventional phone calls. Another reason for maintaining legacy mobile access networks is that many machine-to-machine (M2M) mobile data subscriptions are still based on 2G connections. However, this is expected to change in the coming years as LTE IoT extensions narrowband-IoT (NB-IoT) and Cat-M become operational [22].

In the future, 5G networks will introduce several new concepts, which will have a clear impact on the power consumption and energy efficiency of the mobile access. A conceptual illustration of mobile access via the 5G networks is shown in Figure 4 (Figure adapted from [23]). Massive multiple-input multiple-output (MIMO) [24] has been proposed to improve the area traffic capacity and spectral efficiency [25] of these networks. In massive MIMO, a large number of antennas are used to serve a set of single-antenna user equipment (UE) over the same physical resource blocks. When the number of antennas is much larger than the number of UEs, the signal quality of the UEs can be clearly improved and the transmitted power can be reduced. It is expected that massive MIMO should provide energy efficiency gain over conventional 4G base stations mostly due to the possibility of using low-power RF components [26]. Increasing the number of antennas not only increases the cell throughput but also significantly increases the circuit power consumption. Thus, for a given number of UEs, there is an energy efficiency-optimal number of antennas to be used for transmission and reception [27]. If it is possible to adapt the number of active antennas in a massive MIMO base station to the number of served UEs, significant energy efficiency gain can be achieved [28,29].

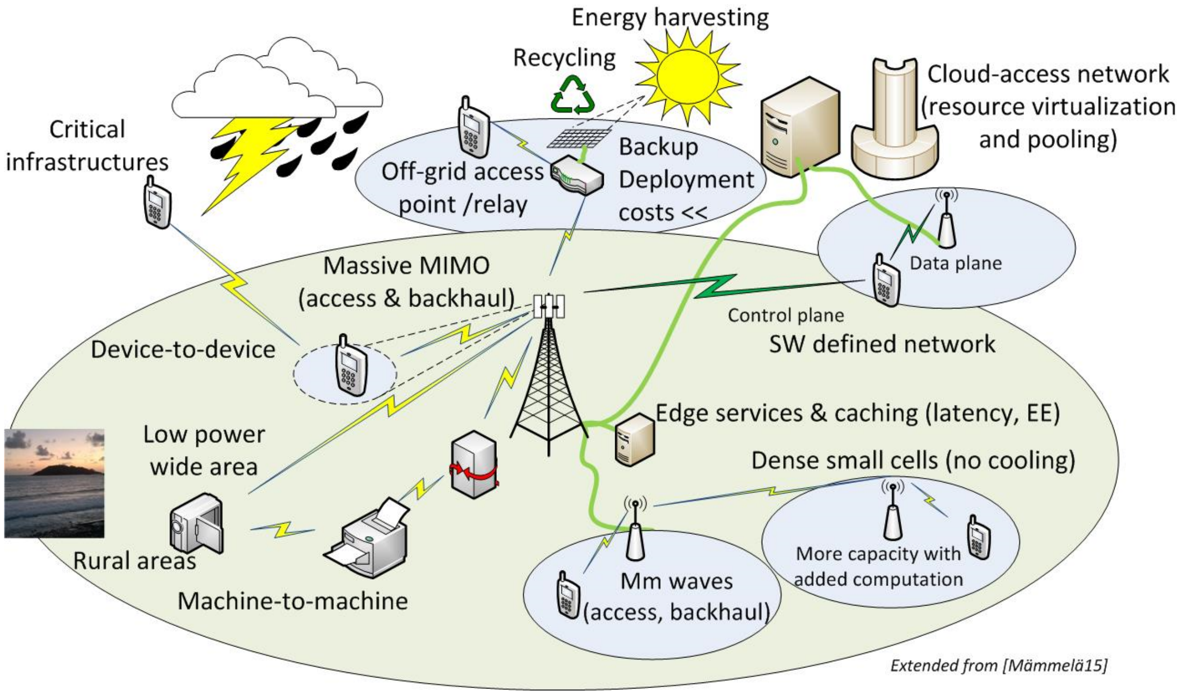

Figure 4. 5G techniques have a clear impact on energy efficiency (EE). (Source: [23], published with permission from the author.)

Dense networks that consist of small cells are essential to the ability of 5G to reach the ambitious ubiquitous user-experienced data rate targets [18]. Small cells can potentially also significantly improve energy efficiency, especially when the sleep modes are enabled during low or no traffic periods [30]. An efficient way to enable the deep sleep modes of small cells is so called dual connectivity where large macro cells and overlapping small cells provide control and data plane services, correspondingly [31]. In this case, small cells can be safely put into deep sleep mode when they are not serving any UEs because the macro cell provides downlink broadcast signalling that enables UEs to connect to the network.

Millimetre wave access is the key to reach really high data rates in small cells through the use of very wide bandwidths (up to 1–2 GHz). Massive MIMO has the potential to fit millimetre wave communications well. The shorter wavelengths at higher frequencies reduce the sizes of large antenna arrays so that they are more practical. Additionally, the high beamforming gain of massive MIMO can partially compensate for the increased path losses that result from millimetre wave propagation [32]. However, even if the energy efficiency associated with millimetre wave transmitters is expected to improve, the power consumption in the RF circuits will increase without careful design. This can be explained by the increased power consumption in the RF circuits, which is dominated by the maximum operational frequency [33]. Cloud-access network architecture has been proposed for 5G to improve scalability and resource efficiency. In a cloud-access network, a baseband unit pool is shared among a large number of cells. This improves the utilisation rate of processing resources and decreases cooling power consumption by cutting down the number of site equipment shelters that require air conditioning [34]. In addition, the centralised control of remote radio units makes it easier to implement cell sleep modes and shaping according to geographical traffic fluctuations [35].

In general, mobile communication is evolving from transmission power domination to computing power intense operation as communication distances are becoming shorter. The related challenges need to be considered carefully both at the base station [36] and mobile terminal side [37]. Due to the increasing role of ICT and mobile communication within our societies, it is important to consider the potential implications of these technological changes from both the point of view of the end-user (consumer) and the environment. And, instead of developing single technologies, services or products, we should think about how these changes affect the whole system in which they operate.

4. Discussion

The environmental impacts of ICT can be assessed from many different viewpoints that can be considered as first-, second- and third order effects, or as direct and indirect effects and structural changes. Direct effects include life cycle impacts related to the manufacturing, recycling and disposal of the various devices needed for ICT and the energy consumed by these devices. Indirect impacts include the changes within the associated production processes, products, and distribution systems that result from the use of ICT. These are often referred to as enabling effects that relate to the use of ICT in different contexts. They may be both positive and negative in nature. Structural and behavioural effects refer to systemic changes within life styles and production and consumption patterns (by individuals and societies at large) that result from the use of ICT. These impacts can be both positive and negative, however, it can be difficult to evaluate their overall impact. This category includes, for example, the rebound effects in which the benefits from more efficient production technologies are offset due to increased production (For more information, see e.g., Reference [38,39]).

Evidence of both positive (enabling effects) and negative effects (rebound effects) related to the increasing use of ICT can be found in the existing literature [40,41]. Consequently, this also underlines the importance of both paying attention to the environmental impacts of ICT in different life cycle phases and developing a broad understanding of potential impacts. Thus, in addition to direct impacts, there is a need to look at the indirect and potential impacts related to behavioural and structural changes in society at large (including changes in consumer behaviour). Due to the rapid changes that are taking place in both consumer behaviour and technology development, this is a topic that requires constant monitoring and research that focuses on different levels. However, it should also aim to synthesise existing knowledge from different point of views. This is also important for avoiding burden shifting from one life cycle phase to another. Altogether, these interlinked combinations make evaluating the potential net impacts of ICT very challenging.

In their review of the direct and indirect energy effects of ICT, Horner et al. [40] concluded that, despite the fact that several studies have been conducted over the last decades, the overall net effect of ICT adoption remains unclear. When considering different electronic/ICT services, a meta-analysis of the studies highlighted how, in principle, ICT has a large energy savings potential, however, realisation of that potential is not assured. One of the reasons for this uncertainty is that the lack of empirical data related to how human users interact with ICT systems hinders the ability to assess the true energy effects. [40]

Within this paper, the potential impact of consumer behaviour on the overall energy demand related to mobile networks and ICT services is discussed. It is argued that, in 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. Discussion in this chapter is focused on the following aspects:

- The impact of mobile networks within the life cycle of electronic services,
- the impact of user behaviour on the life cycle environmental impacts of electronic services and
- the importance of widening the perspective from energy use to resource use and other environmental impacts.

4.1. Role of Mobile Access Networks in the Life Cycle of Electronic Services

Energy efficiency improvements related to mobile networks and network technologies are required to cope with environmental and economic pressures related to growing mobile data usage.

Our findings from Finland point out that, while energy efficiency per transferred gigabyte has significantly decreased, the total energy consumption at a network level might increase in future due to a significant increase in data usage.

Within the service- or device-specific life cycle studies, it has often been difficult to evaluate the role of network energy consumption due to lack of generalised data related to the energy consumption of the network and its different parts. The available estimates of the energy intensity of the Internet have differed at most by a factor of more than 20,000, ranging from 136 kWh/gigabyte to 0.0064 kWh/gigabyte [42]. A large variety within the results has been explained by differences in system boundaries, applied assumptions and the year to which the data applies [18].

Quick, generalised assessments that include network operations are also challenging from a methodological point of view, since energy consumption scales differently in different parts of the network. The energy consumption of the fixed access network, customer premises equipment (CPE) and end-user devices usually scales with time of usage, as it is largely traffic-independent. However, most of the networking devices within the metro and core networks scale with traffic volumes [42]. When mobile access networks are considered, traffic load should also be taken into consideration, since energy consumption is partly dependent on the traffic, even though the idle energy consumption (without data traffic) is also significant.

Within their study on the energy and carbon footprints of the entertainment and media sector in Sweden in 2015, Malmodin and Lunden [9] pointed out that the biggest contributors to the electricity consumption are TVs and TV peripherals, followed by data rooms/centres, PCs and tablets, access networks, phones and CPE [9]. However, in comparison to similar results from 2010, the biggest decrease was observed in terms of the electricity consumption of PCs' and tablets (−35%), while the biggest increase occurred within access networks (+20%). Both fixed and mobile access networks are included in the latter figure. However, the increase in mobile network energy consumption was 150 GWh, while the increase in fixed access networks was 45 GWh within five years [9].

In an earlier LCA study that employed measured data from different network operations, Malmodin and colleagues [10] concluded that the biggest contribution to the ICT-related carbon footprint came from end-user devices (especially personal computers) and that the parts closest to the consumer seemed to be responsible for the majority of the impact. The energy consumption of customer premises equipment within homes was more than the consumption of fixed access and mobile access networks in combination. However, since the data for the study originated from the year 2010, the consumption figures for mobile data were significantly lower than those observed in 2017.

When evaluating the energy footprint of various combinations of user devices and access networks, Schien and colleagues [12] found out that differences between various combinations of devices and networks may be very significant. However, their findings revealed how downloading video content using a mobile phone in 3G network incurs significant energy consumption particularly within the mobile access network, while the impacts on other parts of the value chain are minor. Other significant sources of the energy footprint that were observed in their study included user devices and data centres [12]. Consequently, their findings highlighted the importance of considering the environmental impacts of mobile networks in future studies. The results from our study in Finland underline the importance of this finding, since the increasing use of video content seems to be a major cause of energy consumption in mobile networks.

4.2. Impact of User Behaviour on ICT Related Energy Consumption and Environmental Impacts

Several LCA studies have revealed that the energy consumed during the use phase of different electronic devices is among the biggest contributors to overall energy consumption and often more significant than the consumption of the Internet or the access networks [10,42]. However, the differences between various devices and assumed user habits may be significant. With new energy efficient mobile devices, the production of the device might be a more significant source of environmental impacts than the use phase [43]. Other studies have pointed out that the energy consumption of the mobile access network becomes significant when video content is downloaded using mobile devices [12].

The developments that are taking place in Finland indicate that even though the normalised kWh/Gigabyte consumption is decreasing, the total energy consumption of the mobile networks has remained steady and even slightly increased in comparison to the year 2010. This is due to the rapidly increasing use of mobile devices and data and video content downloads.

The challenges related to energy consumption of mobile networks have also been recognised by the authorities and technology developers. As discussed in Section 3.2, energy efficiency is one of the starting points for the development of the future 5G network technologies. Possible inclusion of home network equipment, smart phones and base stations within the Ecodesign working plan is currently under study, with the overall aim of determining the best policy approach for improving their energy efficiency and wider circular economy aspects [44]. In Finland, 5G networks are currently in the testing phase and reliable estimates of the energy consumption of the 5G networks and related user services can be foreseen in the future.

Even if the energy efficient user devices reduce the direct energy consumption that originates from the use phase, the importance of environmentally conscious user behaviour should be highlighted in future and dedicated studies and guidelines for consumer information purposes should be created. Recent studies have pointed out that increasing consumption (more devices and longer hours of use in combination) might have already exceeded both the energy and resource savings achieved due to the availability of more energy efficient consumer electronics [45]. However, for the moment, the consumption of electronic services is rarely considered within the realms of consumption that has environmental impacts [46].

Currently, one of the most efficient and simple means of reducing the environmental impacts of ICT and related electronic devices is to use the same device longer and to ensure it is recycled when it is no longer viable. Even though this solution sounds simple, acting according to this advice might not be possible, no matter how environmentally conscious consumers aim to be. The low price of devices combined with limited possibilities for repair and fast technology development rather encourage us to buy new devices regularly. It might even be a necessity when the user interfaces or software packages included in old devices become outdated or no repair services exist. Similarly, cheap and efficient mobile connections (with unlimited data usage) allow users to download more and more content from the network, increasing the total energy consumption (often without the consumer even realising it).

A small-scale consumer study that focused on environmental impacts of media use habits was conducted in Finland in 2012–2013. During the time of the study, a huge increase in mobile data consumption could already be recognised and the use of electronic media and ICT devices was rapidly increasing. The findings of the study indicated that, although consumers were, in principle, interested in environmental impacts of different media use habits, they had a lack of knowledge in this regard. Environmental impacts related to electronic devices and ICT use were not considered by consumers who participated in the study. Most often this was due to the fact that the impacts were not visible to the consumer, since they take place out of sight and out of mind [47].

If we extend the view from energy consumption to climate impacts and from ICT-related consumption to other consumption, the total environmental impacts of digital services may still be relatively small. Housing, transport and food are the major source of climate impacts from households in Finland [48]. Currently, three-fourths of an average Finnish consumer's carbon footprint can be traced back to housing, transport and food, whereas approximately one-third is related to other consumption (which includes consumption of various products and services) [48]. Recent studies by the Finnish Environment Institute show that the share of other consumption is growing and the largest growth in the carbon footprint caused by this category was related to the consumption of ICT devices and services, which grew by 139% from 2003 to 2013 [49]. Findings from the UK indicate that the increasing use of ICT is quickly changing our consumption habits, possibly leading to unsustainable practices (see for e.g., Reference [50]). In order to avoid increasing negative impacts (such as greenhouse gas emissions), we should perhaps start thinking about electronic consumption as consumption that has physical impacts and consequences. However, this will require access to information on the environmental impacts of electronic devices and services (which is currently lacking).

4.3. From Energy Consumption to Resource Use and Other Environmental Impacts

When considering ICT-devices and their environmental impacts, most of the information that is currently available relates to energy consumption and greenhouse gas emissions, while studies related to material use or other environmental impacts are relatively rare (See, for e.g., Reference [51]). While a few studies also include environmental impact categories other than climate change, less information on the other potential environmental impacts related to ICT or electronic devices is available (See also [47,52]). It is noteworthy that, although a lot of attention has been paid to climate impacts due to the global need to reduce greenhouse gas emissions, other environmental impacts might be more important on a local level. These include for example impacts related to human and ecotoxicity, however, the assessments of these impact categories often contain a lot of uncertainty [53]. Focusing solely on GHG emissions and energy use may generate misleading results [54] regarding both potential impacts and benefits.

When only energy consumption is considered, network devices (e.g., base stations) usually have a rather long life cycle and energy consumption during operation is often the most important cause of environmental impacts [11]. However, the result is sensitive to the applied assessment method and assumptions related to the use phase. With smaller devices (such as mobile phones), impacts related to the production phase are usually more significant. There is a broad assumption that, in future, issues related to materials and recycling will become more important within the ICT chain (also for the consumer). Paying attention to efficient material use and recyclability is also an efficient means of reducing the consumption related to raw material production and product disposal and recycling phase (See [54]).

In addition to energy consumption, increasing public awareness of the importance of recycling electronic devices is a topic that requires action, both from energy and material efficiency points of view. While the benefits of recycling used devices are often considered within the LCA studies that evaluate the environmental impacts of ICT, the challenges associated with the recycling of waste electronic equipment (WEEE) are a topic of increasing concern in Europe and globally. Currently, out of 9 million tons of WEEE created annually, only 3 million tons are properly recycled. (For more information about the challenges related to WEEE recycling, see, for e.g., Reference [55]). Therefore, many of the potential benefits related to the recyclability of the devices are not achieved. On the contrary, severe environmental and social consequences have been created [56]. Thus, it is arguable that the energy and material saving potentials achieved through technical development may not be realised if more efficient devices lead to increasing use and if the continual development of the devices leads to an increase in the number of devices per user (with shorter life spans per device) and increasing challenges with electronic waste.

5. Conclusions

Our findings highlight how, although the energy efficiency of mobile access networks has significantly improved over the last five years, rapidly increasing data usage and new functionalities have not allowed these savings to realise on the network level. Thus, it is arguable that increasing usage has neutralised some of the achieved energy savings. From the life cycle point of view, use of more efficient technologies has enabled increasing consumption. Whether this will increase total energy consumption in future remains to be seen. However, due to the rapidly increasing amount of connected mobile devices in all sectors of the society, it is a topic that would require further studies and monitoring. In addition to network technology development, we should consider the role consumers play in achieving energy savings.

Due to the importance of the use phase in determining the overall environmental impact related to mobile and electronic services, informing consumers about environmentally friendly use habits should be one of the means of tackling increasing energy demand in the future (together with the development of more energy efficient devices and networks). However, this would require access to transparent and comprehensive data on the environmental impacts of user behaviour. Besides, the focus of the studies should be extended from direct to indirect energy use and resource consumption.

Currently, there is a lack of publicly available data upon which it is possible to make reliable judgements on the energy intensity, emissions, and various environmental impacts of mobile services. Availability of this information would be necessary for developing sustainable ICT products and services. Although our energy efficiency trend estimate is preliminary in nature and is not without a degree of uncertainty, we hope that it provides a starting point for preparing more accurate estimates in the future. An indicative comparison with existing literature points out that our findings are somewhat aligned with previous estimates. To gain a more detailed estimation of the energy consumed by mobile networks and mobile data, a comprehensive bottom-up study based on the measured energy consumption of the different network components should be conducted.

Considering the growing number of mobile devices and increasing coverage of advanced mobile networks (LTE, 4G), mobile access networks should be included in future studies, when estimating the energy intensity of electronic services. If possible, generic models that allow quick estimates of energy consumption should be built. Developed models should take into account the specific features related to mobile access networks and the characteristics of the local network structure.

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