Energy Consumption Estimates of Information and Communication Technology: synthesis and analysis

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Abstract

Energy issues of the Information and Communication Technology (ICT) field have come to the fore in recent years. Perhaps the single most important thing that has led to this situation is the Internet and the way it is expanding: very fast. The Internet infrastructure's constantly growing energy needs have led to a demand for credible energy consumption estimates of ICT equipment: we want to know how much electricity this system spends and what the most energy consuming parts are. If we get answers to these questions we will be able to decide how much we need to decrease the total consumption and where this reduction could be achieved.

This paper presents energy consumption estimates of ICT equipment in Finland and in three important industrial countries, namely the United States, Germany, and the United Kingdom. In addition, a worldwide estimate of the energy consumption of data centers is presented. The results are then analysed, which give answers to questions, such as how valid are the estimation methods used and are the estimation methods comparable with each other.

KEYWORDS: ICT, energy consumption

1 Introduction

The Information and Communication Technology (ICT) industry is nowadays more and more concerned about energy issues. Rapid development and increasing usage of ICT equipment in the past few decades have had a huge impact on the energy consumption everywhere such equipment is installed. As stated by Koomey, the total estimated electricity use for servers worldwide doubled from 2000 to 2005 [5]. Especially the arrival of the Internet and the increasing number of all the devices associated with it, such as routers, switches, hubs and web servers, are increasing electricity use in both office and home environments. Also, wireless telephony is a significant energy consumer at present as stated by Roth et al. [9].

All the things mentioned above are probably the reasons why many energy consumption estimates of ICT equipment have recently been made. This paper will summarise some of these estimates and analyse methods used in them.

We tried to find these energy consumption estimates from as many countries as possible, but that proved to be quite difficult. Almost all reliable and credible estimates were made in the United States and that is why also this paper emphasizes these studies. Luckily, we managed to find some studies also from other countries.

2 Methodology

First, we used the following search engines and data bases in the searching process: ISI Web of Knowledge, JSTOR, ABI Inform Proquest Direct, Elsevier ScienceDirect, and Google Scholar. We used the following search words and every reasonable combinations of them: electricity, energy, consumption, estimate, ICT, information, technology, server, computer, office, network, household, equipment. With the help of these search words and data bases we were able to conclude who the key researchers in this field of study are. That gave us the opportunity to search studies also by the authors' names. We counted as key researchers the following people: J. G. Koomey, K. Kawamoto, K. W. Roth, B. Nordman, and J. Mitchell-Jackson.

Second, we tried to find surveys that needed energy consumption estimates of ICT equipment. By this we mean studies that for example estimate the various effects of increased use of information technology. Kae Takasea and Yasuhiro Murota have written a good example of this kind of study [11]. Then, we looked at references used in them.

Finally, we consulted important scientific journals that deal with energy issues. Those journals were Energy, Energy Economics, and Energy Policy.

3 Evaluated Studies

The findings of some energy consumption calculations are presented in this section

3.1 The United States

In this subsection we will present estimates of how much electricity is consumed by office and network equipment in the United States. In addition, we will consider servers separately.

3.1.1 Electricity Used by Office and Network Equipment in the United States (2001)

Several credible estimates of electricity used by ICT equipment were completed in the beginning of the 21st century. Kawamoto et al. finished their study [2] in 2001. They estimate energy use by office and network equipment in office and non-office settings. They classify office equipment into 11 types (portable computers, desktop computers, servers, minicomputers, mainframes, terminals, displays, laser printers, inkjet printers, copiers and facsimile machines) and each type as residential, commercial, or industrial, according to the location where the equipment is used. They classify network equipment into six types: Wide Area Network (WAN) routers, WAN switches, Local Area Network (LAN) routers, LAN switches, LAN access devices, and LAN hubs.

This study uses the following methodology to calculate the total energy consumption of office equipment. First, it uses shipment data and device lifetimes to estimate the total stock. The shipment data was provided by Information Technology Industry Council (1998) and Appliance Magazine (1999). Lifetimes are obtained from a study made by Koomey et al. 1995. Second, it divides the total stock into residential, commercial, and industrial stocks. Third, it estimates the average power requirement for all equipment in different modes (active, low-power, off). These power requirement estimates are derived from measurements by other researchers and institutions, such as US Environmental Protection Agency. Kawamoto et al. use also their own power requirement estimations for some devices, such as minicomputers and mainframes. They do that because of the wide range of peripherals that might be attached to minicomputers and mainframes which significantly affect the total power requirements of these devices. Fourth, this study estimates the average usage of different modes (active, low-power, off). Fifth, it calculates the unit energy consumption (UEC) by combining the power requirement and the usage of different modes. Finally, it multiplies the UEC by the stock to get the final estimates of residential, commercial, and industrial energy consumption of the office equipment.

This study uses the following methodology to calculate the total energy consumption of network equipment. First, it estimates the domestic sales revenue for one equipment type and divides this number by a representative unit price of the corresponding equipment type. This way the virtual stock number for each network device is calculated. Second, it multiplies the result of the above-mentioned division by the average power of the corresponding equipment type. When these kinds of calculations are made for all network equipment types, the final energy consumption estimate of the network equipment is established.

The results of this study are that the annual energy used by office equipment was about 71 TWh and the annual energy used by network equipment was about 3 TWh in 1999.

3.1.2 Energy Consumption by Office and Telecommunications Equipment in Commercial Buildings (2002)

Roth et al. finished their study [9] in 2002. This is probably the most extensive research which estimates the energy consumption of ICT equipment made so far. Here, we will take a closer look at the findings of it.

This study starts by defining the basic methodology used to develop the desired energy consumption estimates. First, it calculates the annual UEC of a single device taking into consideration different usage modes (active, standby, sleep, off). Then, it obtains or develops the installed base of that device (i.e. the stock) and finally multiplies the device UEC by the stock to get the annual electricity consumption (AEC) for that particular device.

This study uses equipment stocks that are published in other studies, such as industry market reports. Stock estimates come also from sales data and equipment lifetimes. This kind of stock estimation is done by simply summing the sales data over the equipment lifetime. This study applies a combination of household device penetration and judgement to determine the section of the total stock that resides in commercial buildings. In addition, it contains detailed explanation of how the commercial stock of a specific device is estimated but we will not get into such details. Unlike the study made by Kawamoto et al., this study does not differentiate between the energy consumed in commercial and industrial buildings. There are a couple of reasons for that. One reason is that there were no surveys available that would outline the relative density of office equipment in commercial and industrial buildings. Another reason is that it is very difficult to categorize telecommunications equipment into commercial and industial sectors. In many cases this kind of categorization is just impossible.

Roth et al. use in their study four different modes to calculate a device's usage pattern. Usage pattern is the number of hours per week that a particular device operates in a given mode. Active mode means that a device is carrying out its intended operation, for example copier is printing. Stand-by mode refers to a state where a device is ready to carry out its intended operation, for example a monitor is displaying a screen saver. When a device is in suspend mode, it is not ready to carry out its intended operation, but it is still on. Off mode means that a device is turned off but plugged in. This study uses usage pattern data that comes from other surveys.

Roth et al. use the actual power draw whenever possible. Rated power draws, which are reported by manufacturers, represent the maximum power draws that the device's power supply can handle. Using rated power draws leads to overestimation of energy consumption.

The results of this study are that the annual energy used by commercial office and telecommunications equipment was about 97 TWh in 2000. According to this survey, the most energy consuming devices were monitors and displays (22.2%) followed by PCs and workstations (19.6%). Server computers (11.6%) and copiers (9.7%) were also major electricity consumers.

3.1.3 Estimating Total Power Consumption by Servers in the U.S. and the World (2007)

This Koomey's study [5] concentrates on energy consumption estimates of servers in the United States. It updates the server part of the analysis made by Roth et al. Koomey uses in this study the latest IDC (International Data Corporation http://www.idc.com/) estimates on the installed base of servers. The IDC data used in this study includes the total installed base of servers by server class and the total shipment of servers by server class from 1996 to 2010. In addition, the data contains information about the installed base of servers by model and manufacturer and shipment of servers by model and manufacturer. IDC splits the servers into three classes, namely volume, mid-range, and high-end. The server classification is based on the price: volume servers cost less than 20.000$, mid-range servers between 25.000$ and 500.000$, and high-end servers more than 500.000$. Such detailed data was not available to Roth et al.

Koomey uses a similar kind of methodology as Kawamoto et al. and Roth et al. to calculate the total power use of servers. He estimates the average power use of each server and multiplies this result by IDC's total installed base. Koomey estimates the power use per unit by taking the weighted average power of the six most popular models in each class. He uses measured data, on-line server configuration calculators, and estimates specified by manufacturers, to assign power uses of single servers. When no measured power is available he simply multiplies the maximum rated input power of the power supply by factors taken from industry experience to get the actual power use.

Koomey assumes in this study that all installed servers are located in data centers. This means that the total power consumption associated with servers double because data centers also use electricity for cooling and auxiliary equipment. The ratio of total data center electricity load to IT electricity load, that is Site Infrastructure Energy Efficiency Ratio (SI-EER), is typically 2.0. This means that if the servers use one kilowatt-hour of electricity, the infrastructure uses also one kilowatt-hour of electricity.

The result of this study is that the total electricity consumption for all servers in the U.S. was about 23 TWh in 2005. If electricity use for cooling and auxiliary equipment is included, the total electricity consumption rises to 45 TWh. The electricity consumption of the world was about two and a half times bigger than the electricity consumption of the U.S.

3.2 Germany

In this subsection we will present energy consumption estimates from Germany.

3.2.1 Energy usage of mobile telephone services in Germany (2001)

Schaefer et al. did a research on energy usage of mobile telephone services in Germany in 2001 [10]. In the beginning of the 21st century, the number of subscribers in the German mobile telephone sector was over 44.8 million. This number corresponds to more than 54 per cent of the total population, so it is clear that the mobile telephony had become a major factor in total energy consumption in Germany. This study tries to outline how the need of a mobile energy supply influence the energy demand. In addition, it explores the effects of different usage patterns on the total energy consumption.

Network equipment, that is needed to offer mobile telephony services all over the country, consists of Base Transceiver Stations (BTS), Mobile Services Switching Centers (MSC), and Base Station Controllers (BSC). Also, other equipment are needed but the above-mentioned are the most important ones. The energy usage estimation of the network equipment can be done reliably at least in two different ways. One method is to ask the operators for energy costs of network equipment and analyse these costs to get the total energy usage. This method had a big disadvantage because operators were able to provide energy costs only for locations, not for components. The other method, that Schaefer et al. use in this study, is to use the average power consumption of each network component and multiply this number by the stock of the corresponding component. The stock data used by Schaefer et al. comes from press releases, interim reports, and annual reports of all operators. The annual electricity consumption of the network equipment was about 0.678 TWh in 2001. Per subscriber, this means annual electricity use of 15 kWh.

Besides network equipment, mobile telephone service needs also handsets to operate. This study uses three operation modes to estimate the energy consumption of handsets, namely "call", "stand-by", and "off". It is clear that the energy consumption varies substantially depending on the used mode. As stated by Schaefer et al. the power consumption during a call is about 20 times bigger than the power consumption of the stand-by mode. This study assumes that the power consumption is zero when the handset is in off mode. It is important to know how much time each handset operates on each mode. Operators were unfortunately unable or unwilling to give these data to Schaefer et al. so they needed to make other assumptions. This study splits the subscribers into three different profiles. Profiles are private, professional, and prepaid, and they are based on different available tariff options. For example the private users are assumed to speak about 2 hours per month and they are assumed to switch off the handset during nights. The professional users use their handsets much more and the prepaid users are somewhere between the other profiles. This study takes into account also the losses in charging process when estimating the total power consumption of handsets. The annual electricity consumption of the handsets was about 0.0474 TWh in 2001 or 1.06 kWh per subscriber. If all subscribers were considered to be professional users, the annual electricity consumption would have been 0.0906 TWh.

When the consumptions of the network equipment and the handsets are put together, we achieve the annual energy usage of mobile telephone service in Germany in 2001. That is about 0.726 TWh per year or 16.2 kWh per subscriber per year.

3.2.2 Energy Consumption of Information and Communication Technology (ICT) in Germany up to 2010 (2003)

Cremer et al. made an extensive research [1] on energy consumption of ICT equipment in 2003. They estimated the energy demand of modern ICT appliances in Germany up to 2010 and discussed options and potentials for energy conservation of ICT. In addition, they developed an early warning system for ICT energy demand. With the help of this system, it is possible to recognize emerging trends in ICT and to illustrate the influence of these trends on energy demand. We will concentrate here on the part that estimates the energy consumption of different appliances.

Cremer et al. use a model that consists of four components to estimate the current and the future electricity demand of ICT appliances. The components are the stock of the appliances, appliances' electricity consumption in different modes, appliances' operating times in different modes, and saving potentials in implementation of different operating modes.

Cremer et al. use the number of households in Germany to extrapolate the stock of devices located in private households. Estimation of the number of devices in households is based on many statistics, such as official or semi-official statistics, statistics of associations, and statistics of market and opinion research institutes. This study assumes that the number of households in Germany will increase from 38.16 million in 2001 to 38.5 million in 2010. This information is used when predicting future stocks. In addition, a non-linear regression analysis from past trends is used to get a good understanding of the future household equipment.

Cremer et al. find the power consumption values of different household appliances mainly from the literature. In addition, they use their own measurements and expert interviews when no reliable data is available. Power consumption is measured in this study in four different operation modes, namely normal, standby, off-mode, and off. Normal means that a device's energy consumption is 100%. Standby means that a device is waiting for a task. The standby mode can be further divided into ready-mode (energy consumption hardly reduced), standby-mode (energy consumption reduced), and sleep-mode (energy consumption greatly reduced). Off-mode means that a device appears to be off but is still consuming energy, and finally off means that a device is not consuming any energy.

Operating times in different operating modes is the third component of the model. Cremer et al. use a very large set of different surveys and studies to estimate the time that appliances operate in the normal mode in households. Unfortunately, most of the studies do not cover the other operating modes at all. That is why they have to make their own estimations regarding stand-by, off-mode, and off operating modes.

This study uses the above-mentioned methods to also estimate energy consumption of the office equipment. The results of this study are as follows. The total electricity use of ICT equipment in Germany was about 38 TWh in 2001. This equals 8% of the overall electricity consumption in Germany. Cremer et al. predict that in 2010 the power demand for ICT equipment will be about 55.4 TWh.

3.3 The United Kingdom

We were not able to find any comprehensive research on energy consumption of ICT equipment in the UK. However, we did find an interesting study [8] made by Market Transformation Programme (MTP) that involved collecting information about energy consumption of home computers. Here we will present the methodology and the findings of that study.

The key objectives of this study are to outline the times that home computers are in active use, in power management mode and switched off. In addition, this study tries to find out the percentage of computers that have power-management features and what the average energy use figures are in different power-management modes. Finally, it examines how much and to what purposes people use their computers.

Next, we will explain the methodology used in this research. 80 households were recruited from ten regions within England. The researchers attached to the main computer of each household an electrical-power data logger which recorded power consumption at 1-minute intervals. The data collection phase lasted for two weeks. In addition, four questionnaires were administered during the survey. Their purpose was to collect information for example on the age, type, and general specifications of computers.

Results of this study are as follows. Computers are in active use for about 6 hours per day and they use the power-management features for just about 12 minutes per day. In active use the computer's mean power is 0.079 kW, in low-power mode the computer's mean power is 0.030 kW. When computer is switched off, but the mains power is still on, the mean power recorded is 0.003 kW. Although many computers have power-management features, only few people know how to use them. As this study shows, substantial energy savings could be achieved if people started to use these features.

3.4 Finland

Korhonen et al. investigate the electricity use of household and service sectors up to 2010[7]. Their key objectives are to outline methods on how to reduce energy consumption of all kinds of devices. The study includes also sections that deal with energy consumption issues of ICT equipment.

Korhonen et al. use the same kind of methodology as Kawamoto et al. to calculate the energy consumption of ICT equipment. Thus, there is no need to repeat that estimation model. Only with copiers and printers, Korhonen et al. use a slightly more detailed measurements than Kawamoto et al.

The study finds that the energy consumption of office equipment was about 719 GWh in 2000(this number includes energy consumption of laptops, PCs, servers, printers, and copiers). The most energy consuming devices were personal computers (0.468TWh) followed by printers (0.116TWh) and copiers (0.089TWh). According to Roth et al., these equipment compose 72 per cent of the total energy consumption. If the same is true also in Finland, the total annual energy used by office and telecommunications equipment was about 1 TWh in 2000. Energy consumption of ICT equipment in private households was about the same, 1.039 TWh.

In 2003, VTT and Motiva made an interesting study [3] which is also worth mentioning. They investigated electricity consumption of office equipment in one building (Suomen ympäristökeskus). This study was performed by measuring and adjusting copiers, printers, faxes, and PCs. In addition, they discussed ways to reduce the energy consumption of these devices.

3.5 Worldwide

This subsection is reserved for studying worldwide energy consumption estimates.

3.5.1 Estimating Regional Power Consumption by Servers: a Technical Note (2007)

This Koomey's study [4] builds on the previous analysis [5] of total electricity used by servers in the U.S. and the world. The main point of this technical note is to estimate the regional distribution of electricity used by servers in 2005.

IDC does not have installed base data for non-US regions, but it does have shipments data for four major regions other than the U.S.: Western Europe, Japan, Asia/Pacific (excluding Japan), and the rest of the world (excluding the U.S.). Koomey does some calculations and converts the shipments data into installed base data in each non-US region.

The results of his calculations are that electricity used by servers in the U.S. comprise about 40 per cent of the total consumption and in Europe little less than 30 per cent of the total consumption. Japan, Asia/Pacific (excluding Japan), and the rest of the world each fall at between 10 and 15 per cent of the total consumption.

3.5.2 Worldwide electricity used in data centers (2008)

This study [6] builds on Koomey's previous surveys [4, 5]. Its key objective is to include information about electricity use of auxiliary equipment, that are needed to run servers. Koomey begins his study by defining what constitutes a data center. According to Koomey, any space whose main function is to house servers, such as data closets and server rooms, are included as data centers.

Method that Koomey uses in this study is simple. He derives the electricity use of servers from his previous work and then adds data center communications (internal networking), storage, and infrastructure electricity use to that number. Electricity used by data center communications and storage equipment he derives from the US data in EPA (Environmental Protection Agency). For infrastructure electricity use, he uses the SI-EER (Site Infrastructure Energy Efficiency Ratio) which means that if the servers use one kilowatt-hour of electricity, the infrastructure uses also one kilowatt-hour of electricity.

The result of this study is that the total electricity use of data centers were 152.5 TWh in 2005. The distribution between regions is as follows: US (37%), Western Europe (27%), Japan (11%), Asia Pacific excluding Japan (13%), and the rest of the world (13%).

4 Discussion

This section focuses on analysing the benefits and drawbacks of each estimation method presented in the previous section. In addition, we will discuss whether these estimations and estimation methods are comparable with each other or not.

4.1 Validity

We tried to select the most reliable studies to this paper. However, every study seemed to have its own downsides. Here, we will go through each study in the same order as they appear in this paper.

Kawamoto et al. estimated electricity consumption of office equipment and network equipment in the U.S. There were quite a few uncertainties that caught our attention. First, they ignored the power management modes of much equipment entirely. They justified this by pointing to the lack of data on the distribution of different modes. Second, they were not able to estimate accurately the power requirements for servers, minicomputers, and mainframes. Finally, they were unable to get any shipment data for network equipment. Kawamoto et al. estimated that the uncertainties in their study contributed potential error greater than 6 TWh per year.

Roth et al. studied energy consumption of office and telecommunications equipment in commercial buildings. They seemed to have a very wide range of data sources and up to date information about devices' power requirements. In addition, they showed accurately how the energy consumption estimates were obtained for each equipment type.

Koomey estimated the total power consumption of servers in the U.S. and the world. He brought out an interesting point that might have had a substantial impact on the total energy consumption estimate of servers. Large Internet companies, such as Google, often order personal computer motherboards from manufacturers, but use them as servers. The IDC, whose data Koomey used in this study, does not include these kinds of custom servers in their shipment data. It is also unclear that how many companies have used the same kind of PC motherboard customization as Google.

Schaefer et al. did a research on energy usage of mobile telephone services in Germany. They presented a promising method on how to get information about handsets' operating times in different modes (call, stand-by, off). All operators must be able to provide at least the time that each phone is in the call state. That is because they calculate the costs based on the time of calls. However, these data are restricted because operators do not want to reveal any information that might be used to define their customer profiles. Hence, Schaefer et al. had to make their own assumptions concerning the time for different modes. Unfortunately, this reduces the validity of their study. In addition, Schaefer et al. did not take into account the situation when subscribers leave the chargers connected after the charging process.

Cremer et al. made a study about energy consumption of information and communication technology in Germany. This was a very thorough investigation. However, there are a couple of things that Cremer et al. emphasize regarding the part of the study that deals with office equipment. 1. Compared with the household equipment, the available stock data is much poorer. 2. No regular surveys exist about the operating times of ICT appliances in offices.

The study that dealed with energy consumption issues in United Kingdom was quite different from the above studies. Thus, its validity is difficult to evaluate. The results were very accurate, but one has to remember that this study covered power consumption of only 80 computers.

Korhonen et al. investigated the electricity use of household and service sectors in Finland. They used the same kind of methodology as Kawamoto et al. and shipment data of IDC Finland. Hence, the method used in this study should be valid. Also, the stock data provided by IDC are widely

Country	Year	Equipment	Consumption(TWh)
U.S.	1999	Office and Network Equipment	74
U.S.	2000	Office and Telecommunications Equipment in Commercial Buildings	97
U.S.	2005	Servers	23
Germany	2001	Mobile Telephone Services	0.726
Germany	2001	ICT Equipment (office + home)	38
Finland	2002	ICT Equipment (office + home)	2.039
Worldwide	2005	Data Centers	152.5

Table 1: Energy consumption estimates of different studies

respected.

The worldwide electricity use estimates by servers and data centers were also mostly based on IDC shipment data. These data have their own minor weaknesses as we wrote earlier in this section. Inaccuracy in this study is increased also because Koomey assumed that cooling and other auxiliary functions consumed the same amount of energy in all parts of the world. This obviously is not true and it lowers a bit the validity of these studies.

4.2 Comparability

Table 1 combines the results to make the comparison between different studies easier.

This section is much shorter than we expected. When we began the searching process we hoped to find many different estimation methods from all around the world. But as we have said earlier, the found studies used almost identical methods. Hence, in this section we will only compare the consecutive studies in the U.S.

Comparison between Roth et al. and Kawamoto et al. is difficult only in the parts that deal with energy consumption of network equipment. Kawamoto et al. used sales figures to calculate the annual electricity consumption. By contrast, Roth et al. had a more detailed shipment data. On average, Roth et al. got higher annual electricty consumption figures than Kawamoto et al. This can be explained by the updated night-status data and lower power-management enabled rates which were availble only to Roth et al.

The differences between estimations of Koomey[5] and Roth et al. came from different kinds of stock estimations. Koomey estimated the installed base of volume servers to be about 20% greater and the installed base of large servers to be about 10% less than Roth et al. They had also little differences in estimations of power uses per unit. Koomey estimated the servers to consume 16% more energy than Roth et al. in 2000.

Although the estimation methods are almost identical in different studies, there is a noticeable difference in data that is used to define the equipment stocks and the average power consumptions of different devices: the data is not so accurate in older studies as it is in newer ones. Thus, we can say that estimations get better and better as more accurate data comes available.

5 Future Work

The biggest challenge in recent studies has been the lack of accurate and adequate data. This is the most important issue that has to be improved in future studies to make them more reliable and more valid.

For example typical power is in many studies based on factors of rated input power or maximum measured power. These factors are recommendations from manufacturers. Instead, as stated by Koomey, more accurate results will be achieved if a standardized protocol is used to measure the typical power use of devices[5]. Also, more detailed data on effects of new power-saving technologies is needed. That is because this kind of new technology is increasingly being incorporated into the equipment.

Yet another interesting thing, that no one has been studied yet, is the influence of different climates and regions on power consumption. This concerns especially the power consumption of cooling and infrastructure equipment. In the future, we would like to see studies that take into account also this aspect.

6 Conclusions

This paper presented some energy consumption estimates of ICT equipment. It also showed the methods we used in the search process.

Most of the researches that deal with energy consumption estimates of ICT equipment are made in the U.S. We managed to find similar kinds of surveys only from Germany and from Finland. Of course studies might exist that are written in other languages than English (or Finnish), but we were not able to search for these kinds of studies.

The future trend in this field of study is difficult to predict: technology is developing very fast, often making new devices more energy efficient, but on the other hand the number of devices is expanding rapidly. This leads to the fact that in the future ICT equipment might consume more energy in total than today despite the spectacular improvement of technology. Either way, there exists substantial potential for improving the operation of ICT equipment, but more data collection, data analysis, and policy changes are required to realize those improvements.

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