ICT TASK FORCE STUDY

Task 3: Energy Use in ICT systems

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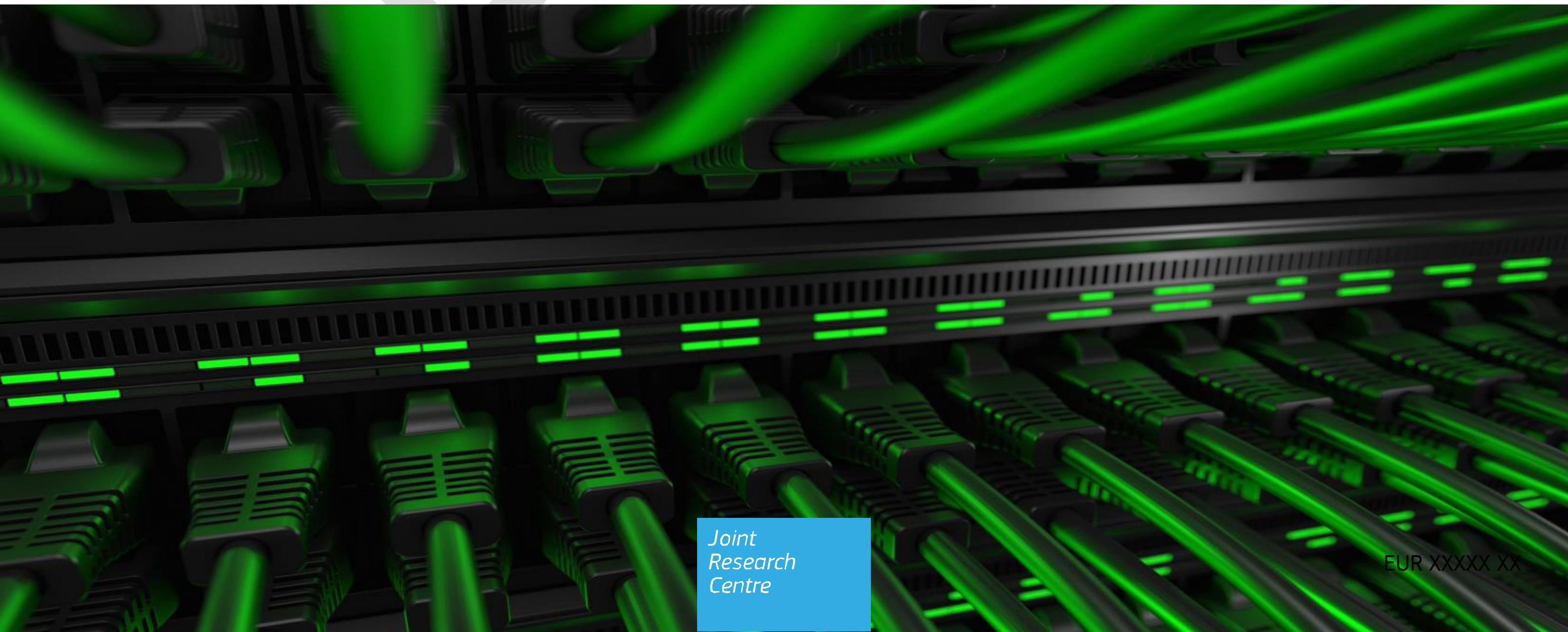
2021



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1 Introduction

Energy consumption of ICT devices is to an extent already being considered in EU product policy. Ecodesign implementing measures have introduced mandatory energy efficiency requirements for ICT products as computers, electronic displays, servers. Other product groups as Complex Set Boxes, Imaging Equipment and Game Consoles implemented voluntary agreements according to the Ecodesign Directive.

Energy labels too have proved successful in encouraging consumers to buy more energy efficient models and manufacturers have responded by producing ever more energy efficient products[1]. Regulated ICT products, such as electronic displays and desktop computers, have significantly improved their efficiency and reduced their energy consumption in the last few years.

The aforementioned approaches have considered energy consumption of ICT devices at their use phase and also on a product-by-product basis. However, with the digital revolution having taken place and still affecting every aspect of economic activity, technological trends such as miniaturisation and cloud infrastructure deployment deem necessary not only the investigation of other phases of ICT lifecycle, but also their consideration at system level.

While using ICT devices is becoming more energy efficient, increasing trends in the energy and carbon footprint related to their production phase (embodied impacts) have received, until now, less attention at both scientific and policy level. At the same time, manufacturing of ICT devices is not currently regulated under the EU Industrial Emission Directive (IED)[2]. It is important to consider that a relevant part of the ICT manufacturing industry is concentrated in Asia, in countries as Taiwan and South Korea, China and Japan, among others.

Several studies reviewed under this task show how the manufacturing process is an environmental hot spot for battery-powered ICT devices and for ICT components as sensors / actuators that are going to be massively deployed in the IoT and Industry 4.0. For these products a dominant part of energy consumption and carbon footprint is related to the production process. Production energy/ embodied carbon can be still relevant for other end-use devices as well, such as electronic displays and desktop computers, especially as integrated circuits such as microprocessors and memory chips are built with increasing transistor density, faster and higher performance. According to Standard & Poor's (2019), the technological hardware and semiconductor industry (the driving force behind the wider electronics industry) is classified among the sectors with the highest environmental and social exposure due to the significant exposure to water and waste management, social and environmental risks related to sourcing minerals such as tin, tantalum, tungsten, gold, and cobalt, which are key materials used in electronic equipment, poor working conditions, and occupational safety standards.

Section 2 of this report provides an overview of the energy demand and carbon emission impacts from the ICT manufacturing stage, focusing mainly into the energy consumption / carbon footprint associated to key components as ICs and sensors. Also other environmental aspects and impacts linked to the manufacturing stage are presented, even though they are not the main focus of this Task.

Several recent studies highlight the lack of transparency in terms of primary manufacturing energy data and the lack of sufficient high-quality inventory data along the lifecycle of ICT devices. Energy use in manufacturing of semiconductors, chips, printed circuit board manufacturing are considered very sensitive parameters for the estimation of the carbon footprint of ICT, especially for battery-powered ICT devices.

The second aspect with regards to energy consumption that is being considered in this Task is an examination of ICT systems as a system. As indicated in Task 2 as relevant for other parameters, studying the energy consumption and demand of ICT systems also requires an examination of the wider range of products and telecommunication services associated with a specific ICT device or service. Furthermore, ever more evident become the trends of digitalization, Internet of Things and subsequently increased data demand which in turn are associated with energy consumption. Indeed, the IEA (2020) points out that, at global level, demand for data centre and network services is expected to grow strongly in the next years, driven, in particular, by the rapidly growing demand for video streaming and gaming. That deems necessary the examination of the sources of this data demand and other future trends related to how ICT systems are used and interact with each other. At the same time, technological development leads to more efficient ICT hardware and equipment

[1] SWD(2015) 139 final

[2] Directive 2010/75/EU of the European Parliament and the Council on industrial emissions (the Industrial Emissions Directive or IED) is the main EU instrument regulating pollutant emissions from industrial installations.

used to provide ICT services. Section 3 of this Task examines the opposite trends around the question of whether ICT as a system leads to an overall increase or decrease of energy consumption. Arriving to reliable forecasts is a challenging task, on one hand due to the dependency of the estimations on the methodology used, and, on the other, the difficulty to grasp the uncertainties associated with a wealth of new technologies and applications that characterise the sector.

Finally, a qualitative assessment of ICT systems in terms of the optimisation effects observed is being provided. The ever-increasing use of Internet of Things devices can lead to energy efficiency gains with the use of sensors, communication protocols and smart devices, These technologies are already revolutionising a number of sectors, with applications ranging from optimisation in industrial manufacturing and the facilitation of RES in energy systems, to consumer engagement in the energy use of home devices and route optimisation in the field of transport. In many cases such applications have already started to take place, such as the wide use of sensors and smart functions in products, while the use of artificial intelligence and energy harvesting are considered expected trends for the future.

2 Assessment of energy consumption from an LCA perspective

2.1 Impacts of manufacturing of ICT

2.1.1 Embodied energy and carbon footprint

Manufacturing of ICT requires energy intensive processes that can have relevant impacts in terms of embodied carbon footprint. From a methodological point of view, the production energy of ICT devices (and the related embodied carbon footprint) can be estimated by a careful lifecycle analysis (LCA) that includes a full inventory of the materials and processes involved, from the material extraction and processing, and the manufacturing of components and assembly, up to the shipment to the final customer.

Most of the ICT manufacturing energy use is associated with the manufacturing of semiconductor components, such as Integrated Circuits (ICs), and other complex components, such as electronic displays and Printed Circuit Boards.

An integrated circuit or monolithic integrated circuit (also referred to as an IC, a chip, or a microchip) is a set of electronic circuits on one small flat piece of semiconductor material that is normally silicon. Digital ICs are the more common variety, mainly because of the vast number of digital devices (not just computers) that make use of them and mainly include MOS memory cells, microprocessors (MPUs), microcontrollers (MCUs), and digital signal processors (DSPs). Perhaps, the single most important digital IC to evolve has been the MPU. This important device, incorporating hundreds of thousands of transistors in an area of about 1-2 square cm^2 or less, has truly revolutionized digital electronic system development. An MPU is the operational core of a microcomputer and digital control system and has broad applications in automotive electronic systems. The MPU incorporates a relatively complicated combination of digital circuits including an ALU or CPU, registers, and decoding logic. It is worth noting that a MCU is different from an MPU in that an MPU contains only CPUs and needs additional peripherals to perform tasks, while an MCU contains CPU, RAM, ROM, etc., that allow it to perform simple tasks independently (Das and Mao, 2020).

The production of ICs is a highly complex sequence of photographic and chemical processing steps whereby electronic circuits are gradually created on a wafer made of pure semiconducting material. From raw material to completion can involve hundreds of steps and can take weeks to complete. This is a highly resource-intensive production process with substantial energy (electricity) and resource use with among the highest environmental impacts per mass unit that exist today for mass produced products (Gupta et al. 2020).

According to Chen et al. (2013) a typical semiconductor fabrication plant can use as much power in a year as about 50,000 homes. In fact, large “megafabs” can consume more electricity than auto plants and refineries. Some facilities have even built their own captive power plants. While the power consumed by semiconductors chips has been reduced significantly in the past decade, improvements in the energy used during the chip production process have lagged behind.

Ultra-pure water is used in semiconductor manufacturing. Water is devoid of organic and inorganic contaminants before being used. This purification process requires energy intensive filtering and treatment. The electricity consumed by pumps, motors, drives and other infrastructure that moves the ultrapure and waste water in, around and out of the wafer fabrication facility is also significant (Water-Energy nexus).

As semiconductor manufacturers are confronted with the need to produce chips with ever smaller feature sizes, operations-driven resource usage is likely to increase dramatically. For instance, the next generation of steppers under development for use in the most advanced wafer fab manufacturing processes employ extreme ultraviolet lithography (EUV). These technologies may require 10 times the power of the previous generation, in part because of a low conversion efficiency (of only a few percent) of an infrared pump laser into the desired ultraviolet output. (Schneider Electric, 2019)

Also display and Printed Circuit boards’ production can be an important contributor of primary energy and electricity consumption for ICT devices’ manufacturing. In general, the manufacturing of these electronic components is much more energy intensive than processes for production of metals (with the exception of advanced processes), plastics and processing of many composites. Indicatively, while production of the latter products roughly falls within a range of 1 to 30 MJ/kg (Duque Ciceri et al., 2010),the primary energy for the manufacturing of a single IoT connectivity IC chip is estimated to be around 40 MJ according to Das and Mao (2020). Furthermore, Annex I reports examples of literature data for the primary energy (and electricity consumption) of semiconductor component production such as ICs and LCD screens, which fall within a range of 200 to 27.000 MJ/cm^2.

At the life cycle level of an ICT device, carbon footprint has two main sources: operational energy consumption (use carbon footprint), and hardware manufacturing (embodied carbon footprint) (Malmodin et Lunden, 2018; Gupta et al., 2020). According to Malmodin and Lunden (2018) the manufacturing stage is more relevant for many end-user ICT devices as this life cycle stage can represent around 50% of the total footprint. This is demonstrated in the Figure 1 below, where embodied carbon footprint is found to be relatively dominant for small battery-powered ICT devices, but also relevant for larger ICT devices as laptops, desktop computers and even for televisions.

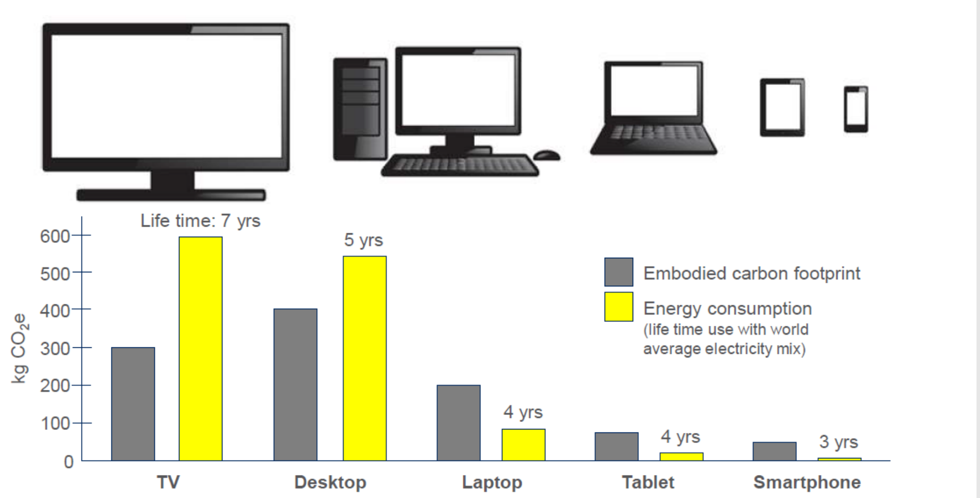


Figure 1: Estimated embodied carbon footprint and use (active lifetime) carbon footprint for common end user ICT devices. Source: Malmodin and Lunden (2018)

As for the embodied energy, according to Malmodin and Lunden (2018), the Integrated circuits (ICs) represent the largest contributor to the carbon footprint for ICT devices. Material extraction, mechanics, displays, and assembly also are responsible of significant carbon footprints (see Figure 2).

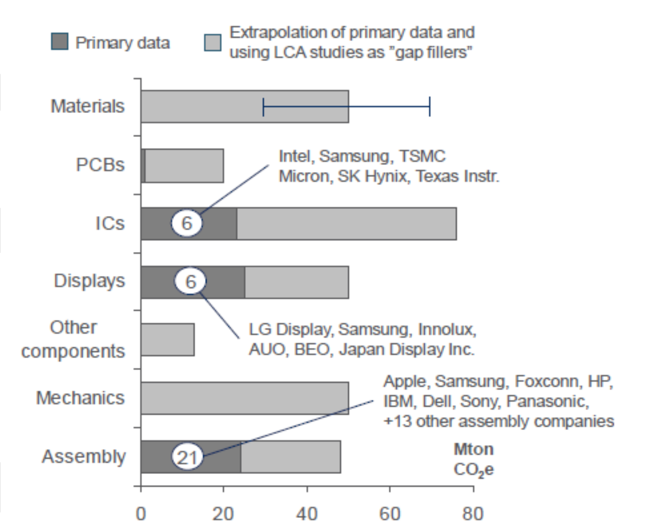


Figure 2: Total Carbon Footprint of the material acquisition and production stage for ICT user devices. The range indicated in materials shows the impact of recycling. Source: Malmodin and Lunden (2018).

The hardware manufacturing stage is the main contributor of the total carbon footprint of battery-powered end-user devices, with roughly 75% of the carbon footprint from hardware manufacturing (Gupta 2020). In particular, most of the emissions come from manufacturing of integrated circuits (e.g., SoCs, DRAM, and storage) (Gupta et al., 2020). That has led to the fact that although carbon emissions from the use phase at device level are decreasing thanks to algorithmic, software, and hardware innovations that boost performance and power efficiency, the overall carbon footprint of computer systems continues to grow for many devices (Gupta et al., 2020).

For several battery-powered devices, the carbon footprint has increased from generation to generation (see Figure 3) mainly due to the increased embodied footprint anfrom production and manufacturing. Figure 3 shows the carbon breakdown over several generations of battery-powered devices: iPhones (from 2008's 3GS to 2018's XR), Apple Watches (2016's Series 1 to 2019's Series 5), and iPads (2012's Gen 2 to 2019's Gen 7). According to Gupta et al., 2020 (figure 3 (top)), the fraction of carbon emissions devoted to hardware manufacturing accounts for 40% of emissions in the iPhone 3GS and 75% in the XR; for Apple Watches, it accounts for 60% in Series 1 and 75% in Series 5; and for iPads, 60% in Gen2 and 75% in Gen 7.

Figure 3 (bottom) shows the absolute carbon output across generations for the same devices. As performance and energy efficiency of both software and hardware have improved over the past few years, the use phase related carbon footprint from energy consumption has decreased. Despite the energy-efficiency increases over iPhone and Apple Watch generations, however, total carbon emissions grew steadily. The increasing outputs owe to a rising contribution from manufacturing as hardware provides more flops, memory bandwidth, storage, application support, and sensors (Gupta et al., 2020).. The opposing energy-efficiency and carbon-emission trends underscore the inequality of these two factors.

Reducing carbon output for the hardware life cycle requires design for lower manufacturing emissions or engagement with hardware suppliers. Alternative/complementary strategies can aim to extend the lifetime of the devices. (Gupta et al., 2020).

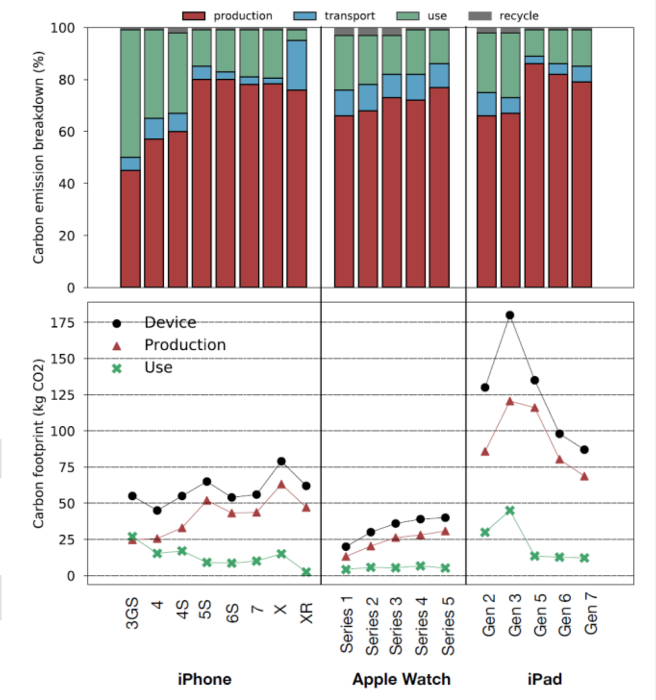


Figure 3. Carbon emissions and breakdown of emissions across generations for Apple iPhones, Watches, and iPads. Source: (Gupta et al., 2020).

From 2017 to 2019, software and hardware optimizations primarily focused on maximizing performance, overlooking the growth trend of carbon footprint.

Figure 4 illustrates the trade-off between performance, measured as MobileNet v1 throughput (i.e., inference images per second) and the manufacturing carbon footprint.

Gupta et al (2020) illustrated the trade-offs (pareto frontiers) between performance and carbon footprint of these devices. Higher performance is achieved through more-sophisticated System-on-Chips (SoCs) and specialized hardware. As highlighted by Gupta et al. (2020), while greater performance is important to enabling new applications and improving the user experience, moving the Pareto frontier down is crucial to design workloads and systems with similar performance but lower environmental impact.

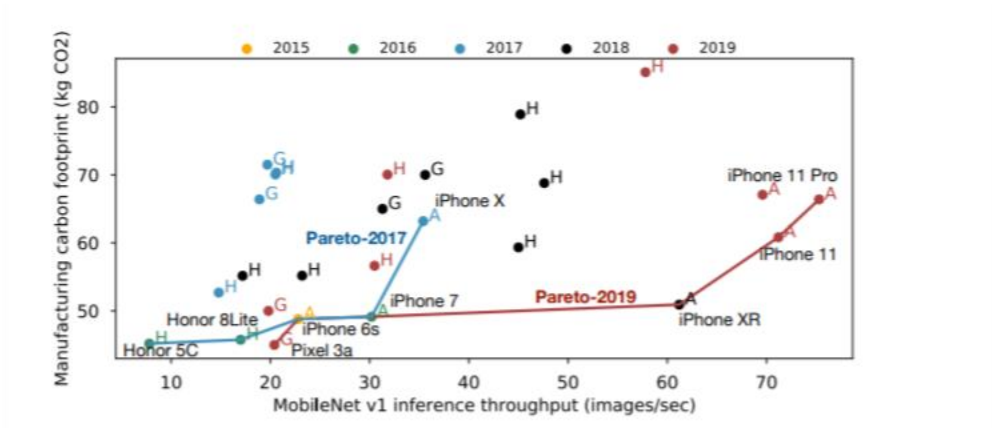


Figure 4. Performance vs. carbon footprint by mobile generation (A represents Apples, G Google and H Huawei).

In the specific case of smartphones, a wider review of carbon footprint studies carried out by Clement et al. (2020) also highlights the relevance of the production phase: 70 ± 12% of the total carbon (Figure 5). The Figure also shows clearly that the ICs, the display and the PCBs are the top contributors for these devices, followed by the casing and the battery. The sources of energy is a major source of variation for the production footprint. Electricity is required at every step of the production, and its share in the IC and PCB production processes is around 50%.

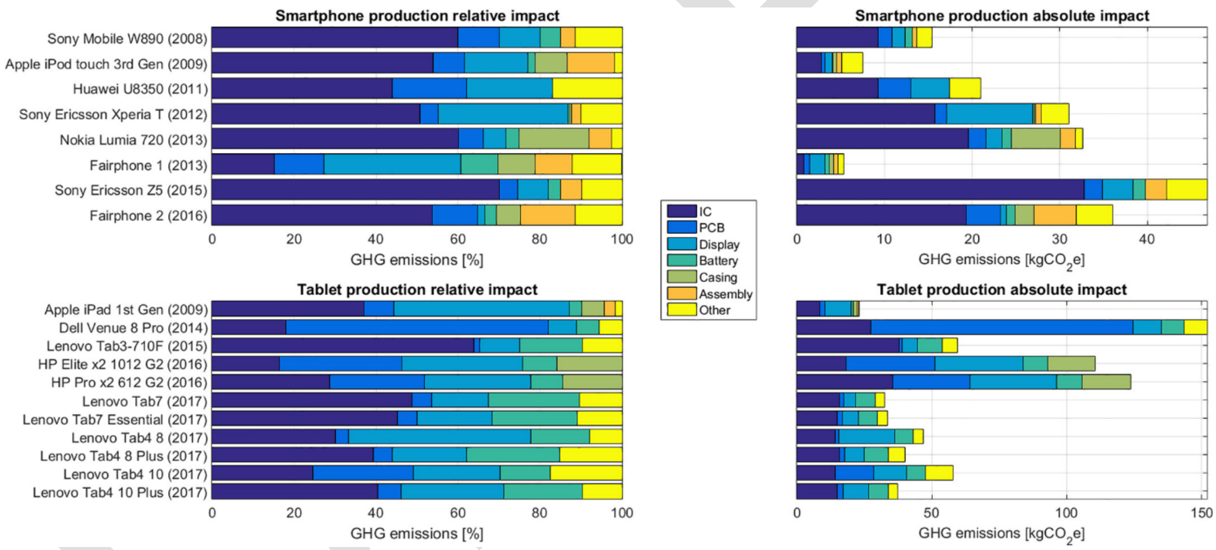


Figure 5: Subcomponents production impact. Source: Clement et al. (2020)

Regarding tablets, Alcaraz et al. (2018) also found that the life cycle environmental impact of tablets is driven by the materials and manufacturing phase, and more specifically the manufacturing of electronic components such as integrated circuits and printed wiring board. The activities that contribute most both to the uncertainty and to the total greenhouse gas emissions are the display and, particularly, the ICs. This result is consistent with other relevant studies in literature that have used a conventional LCA approach. Alcaraz et al (2018) suggest that industry should focus further data collection efforts on integrated circuits, displays, and on improving the granularity of the data.

For data centres devices such as servers, mostly operated by cloud service providers at almost full capacity, the energy consumption of the device during use phase is still considered the most relevant factor affecting the total carbon footprint (Malmodin and Lunden, 2018). Finally, the location of the production plants is crucial as electricity generation accounts for a significant part of the GWP. It has to be considered that consumer's ICTs and components are mainly manufactured in countries such as the Republic of Korea, Taiwan, China, or Singapore, where energy systems are still largely dominated by fossil fuels (resulting in relevant GHG emissions).

According to Itten el al. 2020, switching to cleaner electricity production is essential, particularly in China, where 60% of the material-related climate change impacts of ICT manufacturing are caused. Improved supply chain management is crucial for other regions, which have increasingly outsourced their consumption-based impacts to China (e.g. EU, USA).

2.1.2 Sensors as main drivers of increased primary energy footprint of IoT devices

The deployment of sensors has been characterised as a "sensor tornado", with a growth from 10 million sensors in 2007 to 15 billion micro-electro-mechanical system (MEMS) sensors in 2015[3]. These sensors have enabled the Internet of Things (IoT), in which they act as converters of physical object attributes into representative digital data in the virtual world. The data captured by the MEMS of the IoT, is used to monitor and control the functions and interactions of these objects and is transmitted via internet protocol to the "Edge" or the "Cloud", where the data is stored, categorized, analysed and retrieved from, on demand (Patsavellas and Salonitis, 2019).

An IoT device contains either a sensor or an actuator that interfaces to wired/wireless internet communication, as shown in Figure 6. The key difference between sensors and actuators is that the former changes a physical parameter to an electrical output, whereas it is just the reverse for the latter.

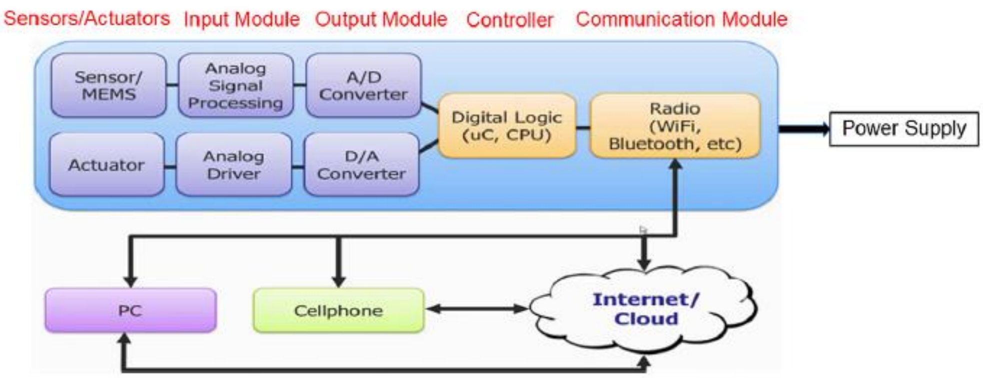


Figure 6: Schematic of an IoT device components flow in a connected economy

An I/O module acts as a mediator and interfaces between the processors (programmable automation controller) and I/O devices such as sensors (input) or actuators (output), and the data type could be either analog or digital. The common types of signal are temperature, humidity, light, pressure, motion, magnetic, vibration, etc.

According to Das and Mao (2020) the total global IoT semiconductor primary energy demand is projected to increase from 2 EJ in 2016 to 35 EJ by 2025, resulting mainly from a substantial projected increase in the manufacturing energy of sensors and connectivity ICs (see Figure 7**Error! Reference source not found.**). According to Das and Mao (2020), IoT connectivity ICs have a significantly higher primary manufacturing energy, e.g., 40 MJ/chip compared with 20 MJ/chip for IoT processor ICs, as Complementary Metal-Oxide-Semiconductor (CMOS) logic chip type is assumed in the former case and a MPU chip for the latter case. With an increasing trend in the technology node of the CMOS logic chip, the increase in its manufacturing energy is projected to be significantly higher in this case, despite market forecasts for both these chip types are projected to be similar by the end of projected period (see Figure 7).

[3] Colin Johnson, C. (2015) "Roadmap to Trillion Sensors Forks", *EE Times*, Available at: https://www.eetimes.com/document.asp?doc_id=1328466#

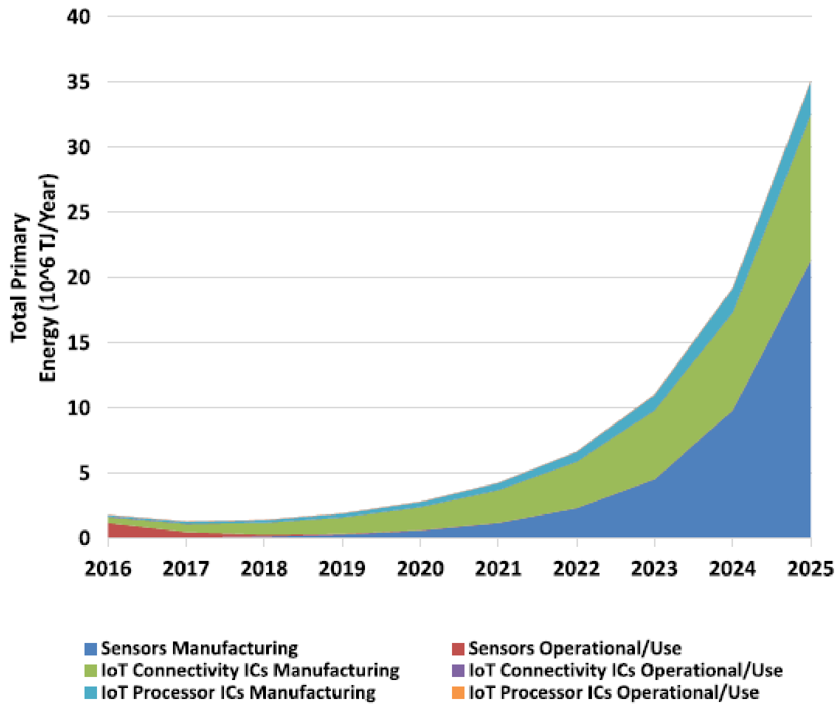


Figure 7: Global total primary energy footprint of electronics in IoT devices.

Additionally, a significantly higher pin count future trend in IoT ICs is assumed that will result in an annual manufacturing energy increase of 0.75 MJ/chip maximum in the case of IoT sensor ICs. The primary energy demand for different IC package methods is shown in Figure 8 (Das and Mao 2020).

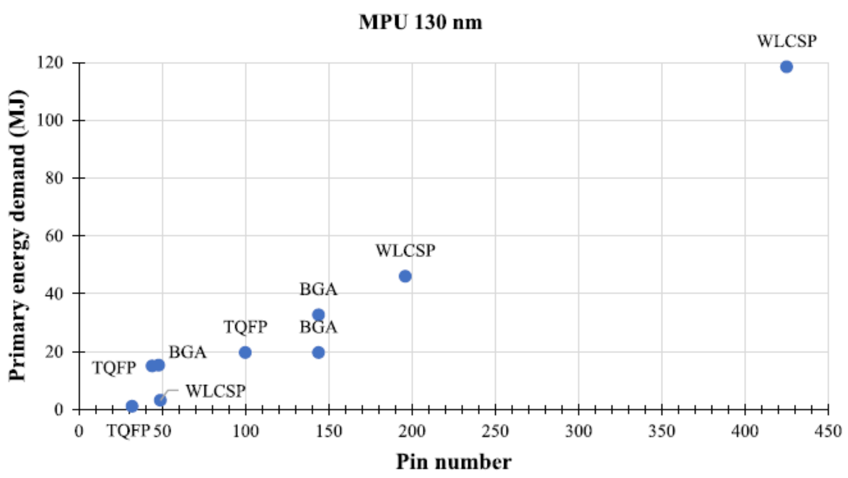


Figure 8: Primary energy demand of 130 nm MPU with different package methods.

2.1.3 Challenges in assessing carbon footprint of semiconductors

According to Clemm et al. (2019) semiconductors, despite contributing to a significant share of the total environmental impacts incurred by the manufacturing of electronic equipment, are frequently challenging to model in LCA studies, also as manufacturers of electronic equipment do not commonly publish detailed data on the latest fabrication processes. Also in the case of Das and Mao (2020), primary manufacturing energy data on chips has been limited to date due to difficulties in obtaining manufacturing-process level data on the dynamic technology nature and the increasing complexity of the technology.

Vasan et al. (2014) found reasons to believe that embodied carbon footprint could be underestimated in individual LCAs of electronics as a result of the inconsistencies arising from the system boundary selection methods and databases, the use of outdated LCA approaches, and the lack of supplier's emissions-related data.

Alcaraz et al. (2018) consider that the amount of information required to model the carbon footprint can be reduced by targeting the activities that have the most leverage to reduce uncertainty,

Integrated circuits (ICs) are frequently packaged into polymeric housings, which complicates the process of gathering information on the semiconductor itself. To appropriately model semiconductors in LCA studies, the area of silicon contained within the IC package needs to be known, as the area of processed semiconductor material is considered the most appropriate parameter to estimate environmental impacts of the complex clean room production processes including lithography, etching, and metallization steps. Clemm et al. (2019) describe various techniques that can be applied to obtain such information to differing degrees of certainty. **Error! Reference source not found.**Figure 9 shows the photo of a packaged IC from a smartphone mainboard as well as an X-ray image of the same IC, revealing the internal structures that can be used to estimate the semiconductor area contained in the package. In this particular case, the X-ray image shows that an estimation made from only judging the package itself would easily lead to an overestimation of the actual area. Destructive methods, such as decapping, can reveal the actual die size, however, the X-ray image is a good starting point to reduce uncertainty of assumptions regarding semiconductor area in an IC.

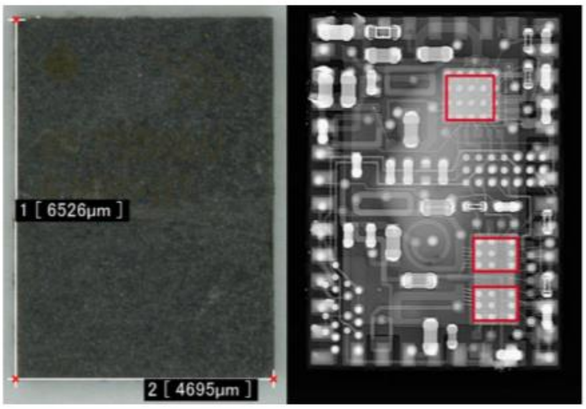


Figure 9: Photo of a packaged 3G/4G power amplifier IC from a smartphone mainboard (left) and X-ray image of the same component indicating it is a module with three smaller dies (highlighted in red boxes) and various passive components. Source: Clemm et al. 2019

During the Ecodesign Preparatory Study for Smartphones, Fraunhofer IZM et al., (2020) remodelled semiconductor datasets based on data by highly relevant semiconductor manufacturers (Table 1). Data furthermore is scaled per cm² of die area, which is considered a much more accurate scaling parameter than the packaged IC weight as applied in the standard EcoReport datasets. This is particularly the case for storage chips where several dice are stacked in one package and actually the package size (and weight) is actually the same across all storage specs, but differing in size of integrated semiconductor area. Data for upstream wafer manufacturing is based on industry data compiled in ongoing research projects. Notably, the ICs are much more primary energy and carbon footprint intensive than the other components. More literature data are available in Annex 1.

Table 1: Additional datasets specific to the product group mobile phones, smartphones and tablets, per kg or per 1000 cm²

	Name material	Recycle %*	Primairy Energy (MJ)	Electr energy (MJ)	feedstock	water (process)	Water (cooling)	Hazardous waste	Non Hazardous Waste	Greenhouse Gases in GWP100	Acidification (emissions)	Volatile Organic Compounds (VOC)	Persistent Organic Pollutants (POP)	Heavy Metals	Polycyclic aromatic hydrocarbon	Particulate Matter (PM, dust)	Heavy metals (to water)	Eutrophication
unit	New Materials production phase (category **'Extra'**)	%	MJ	MJ	MJ	L	L	g	g	kg CO2 eq.	g SO2 eq.	mg	ng i-Teq	mg Ni eq.	mg Ni eq.	g	mg Hg/20	mg PO4
100	**Flex PCB Ni/Au-Finish 1-layer per cm²**	**0**	163.70	70.88	-	1,787.50	-	0.00	91.18	7.80	28.33	2.69	-	72.21	-	1.29	3,459.79	45,156.88
101	**Flex PCB Ni/Au-Finish 1-layer, double-sided per cm²**	0	228.43	130.52	-	1,868.75	-	0.00	122.41	10.36	38.32	3.02	-	76.88	-	1.31	4,685.63	45,983.06
102	**FR4 PCB Ni/Au-Finish 4-layers per cm²**	0	345.01	227.96	-	2,087.50	-	0.00	173.34	15.13	51.85	3.72	-	84.51	-	4.41	6,690.93	47,637.17
103	**FR4 PCB Ni/Au-Finish 6-layers per cm²**	0	491.79	354.38	-	2,256.25	-	0.00	239.38	21.05	68.64	4.57	-	93.52	-	5.61	9,279.42	49,596.40
104	**FR4 PCB Ni/Au-Finish 8-layers per cm²**	0	631.82	480.80	-	2,431.25	-	0.00	305.43	26.57	84.28	5.38	-	101.79	-	6.44	11,853.28	51,335.00
105	**FR4 PCB Ni/Au-Finish 10-layers per cm²**	0	771.85	607.22	-	2,606.25	-	0.00	371.47	32.09	99.92	6.19	-	110.07	-	7.26	14,427.14	53,073.60
106	**FR4 PCB Ni/Au-Finish 12-layers per cm²**	0	918.64	733.64	-	2,775.00	-	0.00	437.52	38.01	116.71	7.03	-	119.08	-	8.46	17,015.63	55,032.82
107	**FR4 PCB HAL-Finish 1-layer per cm²**	0	152.39	72.56	-	343.75	-	0.00	92.04	7.12	21.79	1.68	-	54.94	-	3.33	1,730.83	3,787.96
108	**FR4 PCB HAL-Finish 1-layer, double-sided per cm²**	0	217.12	132.20	-	425.00	-	0.00	123.28	9.68	31.78	2.01	-	59.60	-	4.05	2,956.67	4,614.14
109	**LCO-Battery (Lithium-Cobalt-Oxid)**	0	267.31	-	-	-	-	-	453.21	22.88	136.38	57.23	-	235.39	-	15.82	1,825.35	18,959.24
110	**NiMH battery (AAA)**	0	230.00	-	-	34.66	55.00	19.60	600.54	19.00	764.00	0.12	2.16	7.66	204.65	35.61	74.23	27,400.00
111	**LCD display, smartphone, per cm²**	0	255.83	245.15	-	93.33	-	91.20	112.68	19.59	64.98	5.09	-	119.05	-	6.50	-	12,211.47
112	**LCD display, tablet, per cm²**	0	213.19	204.29	-	77.78	-	76.00	93.90	16.33	54.15	4.24	-	99.21	-	5.42	-	10,176.22
113	**AMOLED panel per cm²**	0	363.93	245.15	-	93.33	-	91.20	112.68	14.27	64.98	5.09	-	119.05	-	6.50	-	12,211.47
114	**Glass per g**	0	27	21.816419	0	24.725275	0	0.8065028	40.580514	2.45	9.012502967	0.0131819	0.2294104	0.5305702	0.000859	0.1925659	0.1186721	1.076105625
115	**Silicone**	0	156.63	24.56	42.64	19.00	384.00	0.00	1,434.00	6.86	14.82	-	-	-	0.12	15.00	0.04	1,860.00
116	**NdFeB magnet**	0	330.00	3.42	0.11	39.33	-	-	2,582.28	27.60	440.00	0.20	39.00	36.00	0.10	124.00	2.00	79.00
117	**IC, SoC per cm² die area**	0	33,764.43	27,050.65	-	22,975.39	27,132.00	42,695.42	52,041.86	3,017.45	56,582.32	658.01	-	84,879.02	-	1,216.30	124,862.73	1,556,788.39
118	**IC, DRAM (50% of SoC) per 1cm² die area**	0	16,882.22	13,525.32	-	11,487.69	13,566.00	21,347.71	26,020.93	1,508.72	28,291.16	329.00	-	42,439.51	-	608.15	62,431.37	778,394.19
119	**IC, NAND (60% of SoC) per 1cm² die area**	0	20,258.66	16,230.39	-	13,785.23	16,279.20	25,617.25	31,225.12	1,810.47	33,949.39	394.80	-	50,927.41	-	729.78	74,917.64	934,073.03
120	**Generic IC per 1cm² die area**	0	26,730.18	21,415.10	-	18,188.85	21,479.50	33,800.54	41,199.81	2,388.81	44,794.34	520.92	-	67,195.89	-	962.90	98,849.66	1,232,457.47

Please note that although the dataset reads per cm² / per g in column “Name Materials” the values in this table are actually expressed per 1000 cm² or per kg.

2.2 Other environmental impacts

The manufacturing of semiconductor components that are present in all ICT devices is not only relevant from the primary energy and global warming point of view. Other environmental issues, including the water-energy nexus, should be considered.

Villard et al. (2015) conducted eight interviews with actors of environment strategies and policies in a leading semiconductor company and based on this interview results (tables below) also additional environmental impacts as water stress / water toxicity and resource depletion are highlighted as relevant impacts from the semiconductor industry (see **Error! Reference source not found.**).

Table 2 Expert ranking of environmental concerns in manufacturing plants. Source: Villard et al. 2015

IMPACTS	REPORTING	FRONT END SITES	BACK END SITES	REASON FOR IMPACT CONTROL: DESIRABLE LEVEL OF SITE RESPONSIBILITY
Toxicity in water	1	++	+++	Many dangerous chemicals are consumed; the risk of toxic effects on health and ecosystems by waste water exists
Global warming	1	+++	+++	Direct - perfluorocarbons (PFCs) - or indirect – energy - emissions The level of severity depends on the efficiency of PFC treatment units Intensive use of electricity
Resource depletion	1	+++	+++	Intensive use of raw materials
Water stress	0	+++	+	Intensive use of ultrapure water
Water Acidification	0	++	+	Many acids are consumed; the severity level depends on the sensitivity of local ecosystems and the efficiency of waste water treatment plants
Eutrophication	1	= / ++	+	Many acids are consumed; the severity level depends on the sensitivity of local ecosystems and the efficiency of waste water treatment plants
Air acidification	1	+ / ++	=	A few acidifying gases are used; the majority of emissions is controlled by air treatment units; site-dependent
Summer smog	1	++/+++	++	Emissions in air due to general plant functioning; the severity level depends on the sensitivity of local ecosystems and the efficiency of Volatile Organic Compounds (VOCs) treatment units
Human health	0	+	+	A few dangerous substances have to be managed for worker safety
Waste	1	=	+	Considerable quantity of plastic waste; variable rate of recycling
Noise	0	=	=	
Ozone layer depletion	0	=	=	
Toxicity in air	0	=	=	A few toxic gases are consumed; All are under control by air treatment units
Land occupation	0	=	=	
Toxicity (soil)	0	=	=	
Smell	0	=	=	

2.3 Performance indicators and benchmark

The evidence from scientific literature described above indicates the necessity of having more transparent data on the energy demand and environmental performance of the semiconductor manufacturing, including the size and type of the ICs included in ICT devices.

The Commission (European Commission, 2019) has recently produced sectoral best environmental management practices (BEMP) (Commission Decision (EU) 2019/63) applicable to electrical and electronic equipment manufacturing sector, have established some environmental performance indicators for electronic equipment manufacturing, even though benchmarks of excellence have not been established (Table 3).

Table 3: BEMP applicable to electrical and electronic equipment according to the Commission Decision (EU) 2019/63

	Environmental performance indicators	Benchmarks of excellence
Cleanroom activities	(i1) Energy use in the cleanroom for printed circuit board manufacturing (kWh/m^2 of processed printed circuit board) (i2) Energy use in the cleanroom for semiconductors and/or integrated circuits manufacturing (kWh/cm^2 of silicon wafers) (i3) Air Change Rate (number/hour) (i4) COP (Coefficient of Performance) of the cooling equipment installed (kWh cooling energy produced/kWh energy used) (i5) Water conductivity (µS/cm)	Not available
Cooling	(i6) Coefficient of Performance (COP) for individual cooling equipment (kW of cooling power provided/kW of power used) (i7) Coefficient of System Performance (COSP) including the energy required to run the supplementary equipment of the cooling system, e.g. pumps (kW of cooling power provided/kW of power used) (i8) Use of cooling cascades (Y/N) (i9) Use of free cooling (Y/N) (i10) Use of heat recovery ventilators (Y/N) (i11) Use of absorption chillers (Y/N) (i12) Energy use of the cooling system per unit of turnover (kWh/EUR)	Not available
Soldering operations, (especially relevant for the production of printed circuit boards (PCB)).	i13) Total energy demand per surface unit of printed circuit board processed (kWh of electricity/m^2 of PCB) (i14) Nitrogen consumption per surface unit of printed circuit board processed (kg of nitrogen/m^2 of PCB)	Not available

2.4 Discussion

Several life cycle studies show that, for small ICT (battery powered) devices as smartphones and tablets, the energy and carbon footprint impacts are mostly related to the production stage (embodied carbon footprint >75% of the total carbon footprint). Similar results are expected for IoT devices with high-tech sensors that are expected to increase their embedded energy and embodied carbon footprint of ICT despite a clear trend for energy efficiency improvements in their use stage.

For other ICT devices, such as servers for cloud services, operated at almost full capacity, the energy consumption of the servers during use phase is by far the most relevant aspect to be addressed (discussed in the following section). As general rule, manufacturing dominates emissions for battery-powered devices, whereas operational energy consumption dominates emissions from always-connected to the mains devices (Gupta et al., 2020).

In order to better understand the relevance of embodied impact for other ICT more data are needed related to the production Energy (PE) of device components and impacts of key components as Integrated Circuits, sensors, PCBs, screen.

However, based on the discussion above, Table 4 provides a qualitative assessment of the relative relevance of the embodied energy / carbon footprint compared to the energy / carbon footprint due to the use phase is presented below (see Table 4).

Table 4: Relative relevance of the embodied energy / embodied carbon footprint compared to the energy / carbon footprint due to the use phase for the products in the scope of this study

Product Group		Embodied energy and embodied Carbon Footprint Relevance (see note below)
Data Centre Devices (e.g. servers, storage devices, Networking devices as switches/routers)		Low
Telecommunication Network Broadband communication equipment		Low
End use Devices	Electronic displays	Medium
	Audio/video devices	Medium/High (High relevance for small battery powered devices as mp3 players or cameras)
	Computers	Medium/High (High relevance for small battery powered devices as notebooks and tablets)
	Imaging Equipment	Low
	Home / Office Network Equipment	Low
	ICT in public Space (e.g. ATMs, cash registers, security camera)	Low
	Building Automation and Control	High
	Industrial Sensors	High
	Uninterruptible Power Supply (UPS)	Low
	Audio Equipment (e.g. loudspeakers, wireless speakers, smart speakers, soundbars …	High
Explanatory note: Relevance of embodied energy and carbon footprint The relevance of the embodied energy and embodied carbon footprint is expressed in relative terms, compared to the energy consumption in the use stage:		

- “Low” means that indicatively < 25% of the device embodied energy / carbon footprint is related to the production stage of the ICT device
- “Medium” means that between 25% and 50% of the device embodied energy / carbon footprint is related to the production stage of the ICT
- High means that more than (>50%) of the device embodied energy / carbon footprint is related to the production stage

3 Analysis of the energy consumption linked to the use of the ICT end-use device (telecommunication network / data processing)

3.1 The challenge of capturing the energy use of the internet

Different parts of ICT systems communicate via networks, and each action instigated by an end device user (from messaging and uploading files to streaming videos and games) mobilizes not only the end device itself, but also the network infrastructure that provides the connection and the data centre infrastructure that computes, stores and transmits data related to deliver the requested service. As different parts of the ICT system operate to deliver the service, each one is associated with energy consumption. According to Andrae and Endler (2015), electricity usage from ICT is divided into four principle categories:

(i) consumer devices, including personal computers, mobile phones, or TVs;

(ii) network infrastructure;

(iii) data center computation and storage; and lastly

(iv) production of the above categories[4].

In an attempt to examine the energy consumption of ICT systems overall, a methodological challenge arises. How is this energy consumption associated with internet use and applications allocated amongst parts of the ICT system? In other words, as several parts of an ICT system contribute to the delivery of a service, how much does each part contribute to the energy use of the whole system?

Coroama and Hilty (2014) define the metric of **internet energy intensity** as the energy consumption per data transferred. Using the example of video streaming, which, as noted above, has a major impact on data demand, they further underline the importance of system boundaries. Three different approaches in the literature are identified:

- Top–down approaches, taking into account the total electricity consumption estimated for the Internet and the Internet traffic for a region or a country within a defined time period. Dividing the former quantity by the latter yields the average energy consumption per data transferred.
- Model-based approaches, which combine modelling parts of the Internet (i.e., deployed number of devices of each type) with manufacturers' consumption data on typical network equipment to arrive to the overall energy consumption.
- Bottom–up analyses, which are based on direct observations made in one or more case studies, leading to energy intensity values for specific cases, and a discussion of the generalizability of the results.

The difference in methodology and the variation in terms of results are one of the reasons that make future estimations on energy use challenging. On one hand, bottom-up studies better account for factors such as service demand growth, different types of equipment, energy efficiency, and market structure (Masanet et al 2020). On the other hand, such studies can be very time consuming, making top-down studies more suitable when data on how devices and their usage transform over time is scarce (Andrae and Edler, 2015).

Related to these challenges are also uncertainties related to whether all data flows are captured by studies, considering data centres come in different types and sizes, networks of different ownership status (private vs public) are used and ICT system parts have multiple functions not easily attributed to one action (e.g. data centers are used for data storage and transmission but also computing) (Bashroush, 2020; Mayers et al, 2015).

The following section presents data from studies following both top-down and bottom-up approaches, and examines major technologies that shape future energy consumption trends.

3.2 Trends in ICT system energy use

Whether the ICT sector's total energy consumption increases or decreases depends on which of the two effects prevails – the **growth of the sector** or the **increases in energy efficiency** (Lange et al, 2020). It is therefore an issue of whether the level of decoupling of energy use from growth is sufficient.

[4] The energy demands for the production of the product categories have been studied in part 3a

A useful basis for the investigation of elements of each trend (or "drivers") is provided by Masanet et al (2020) in the following Figure, which refers to energy use of data centres globally. However, due to the central role that data centres play in determining and delivering data growth, as well as the interrelations between the parts of an ICT system devices and network, these drivers can be considered for the entire ICT system, as presented in 10 below.

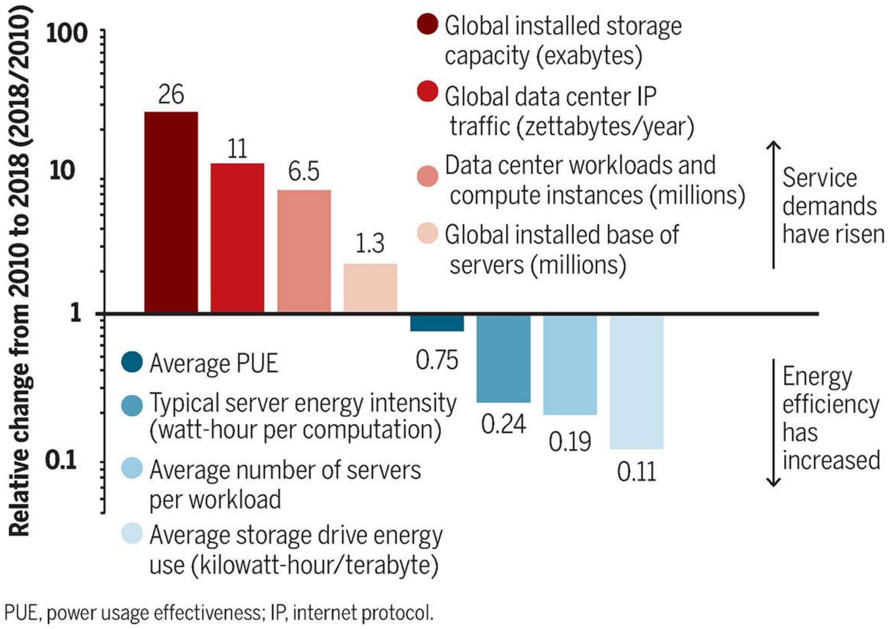


Figure 10: Trends in global data center energy-use drivers

This structure can be extrapolated to the entire ICT system as demonstrated in Table 5. (Masanet et al, 2020)

Table 5: Trends in global ICT system energy-use drivers (adapted from Masanet et al (2020))

	Data Centers	Network Infrastructure	Consumer Devices
Growth demand	Installed storage capacity	Fixed broadband speeds	Internet users / subscribers
	Data centre IP traffic	Mobile network speeds	Networked devices/connections
	Workload/ compute instances	Network data traffic	Video Resolution
	Installed base of servers		Traffic growth driven by gaming and cryptocurrency
Efficiency	Power Usage Effectiveness	Energy intensity of data transmission	Device energy efficiency
	Typical server energy intensity	Energy efficiency of antenna base stations	
	Average number of servers per workload		
	Average storage drive energy use		

Following a top-down approach, Andrae and Endler (2015) expect an increase of annual energy consumption mainly driven by the transfer of use-stage electricity from consumer devices to the networks and data centers (see Figure 11).

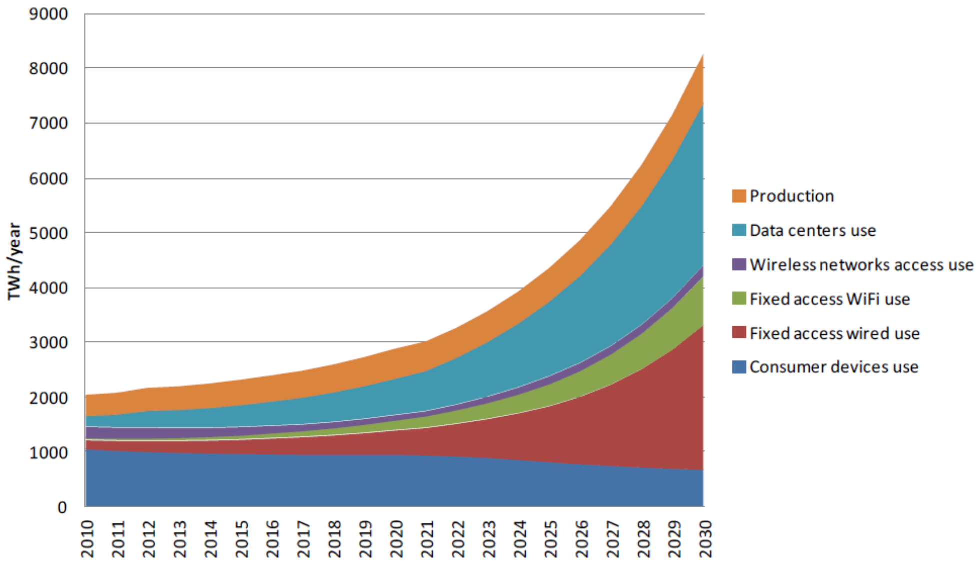


Figure 11: Expected electricity consumption scenario from ICT sector according to Andrae and Endler (2015)

Other sources argue that the aforementioned growth in data demand is compensated by increase in efficiency, driven by technical developments across all parts of the Internet, as well as use of improved energy management techniques in data centres and network operators (Policy Connect, 2018). Such efficiency refers firstly to energy efficiency of IT devices themselves, including servers and storage drives which has improved substantially. Secondly, the energy intensity of the internet use has been significantly reduced. Third, most compute instances have migrated from traditional data centres to much more efficient cloud and hyperscale data centers. (Energy Innovation, 2020). Figure 12 below demonstrates these efficiency gains when assuming a doubled (relative to 2018) computing demand (Masanet et al 2020).

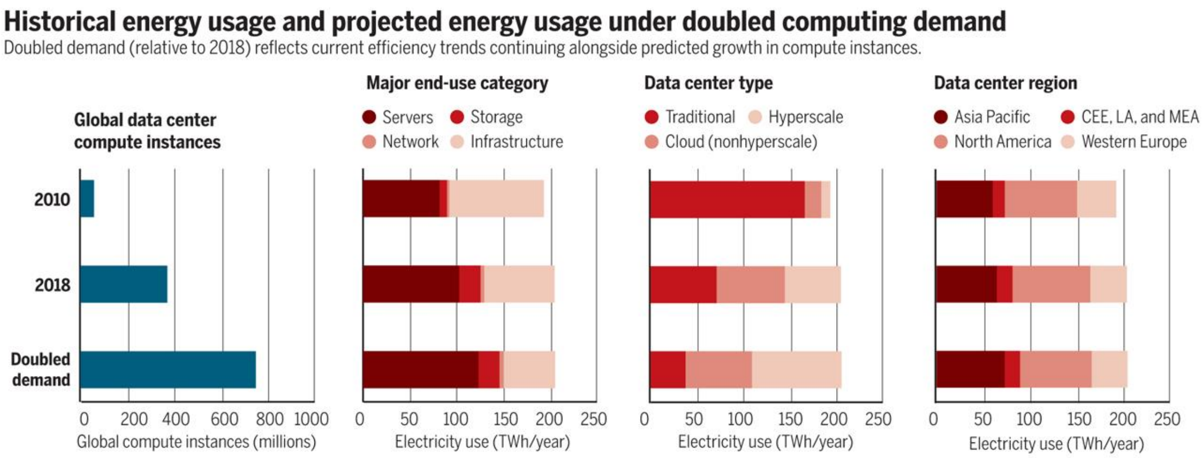


*Figure 12: Historical energy usage and projected energy usage under doubled computing demand**
**Doubled demand (relative to 2018) reflect current efficiency trends continuing alongside predicted growth in compute instance*

In the following sub-sections, parts of ICT systems are examined separately.

3.3 Data centres

The importance of data centres within ICT systems have been outlined in Task 2. Data centres comprise of a number of IT devices in order to provide the services of data computation, storage and connection to the network. Energy use is also associated with cooling equipment necessary to remove the heat generated by the aforementioned devices, as well as the infrastructure necessary to power them (Energy Innovation, 2020). In fact, around 55% of data centre energy consumption originates from its IT devices, while 45% from supporting equipment, as demonstrated in Figure 13 below (AGCoombs, 2018).

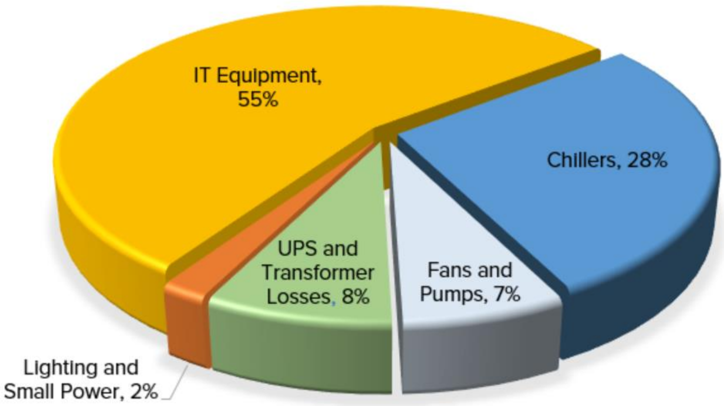


Figure 13: Average allocation of energy consumption between the different components of a data centre. Source: AGCoombs, 2018

Estimations stemming from literature are not conclusive with regards to future energy consumption of data centres. That difference in results can be explained by the variations in methodological approaches described in Section 2, with bottom-up studies showing reductions in energy use. Figure 11 above illustrates the efficiency improvements in data centres which have resulted in small annual electricity use despite increases of computational instances in recent years.

F

Two main factors are identified as keeping energy demand approximately flat.

One factor is efficiency improvements for servers, storage devices and network switches, as well as in terms of infrastructure related to equipment other than IT.

With regards to IT equipment efficiency, Masanet et al (2020) report that despite the increase in compute instances (demonstrated in F1 above and also in the table below), the energy use per compute instance, the energy consumption did not increase proportionally, leading to the conclusion that the energy intensity of global data centers having decreased by 20% annually since 2010.

Table 6: Global workload and compute instances 2014-2021. Source:VHK and Viegand Maagøe, 2020

Workload and compute instances (in millions)	2014*	2015**	2016	2017	2018	2019	2020	2021	CAGR 2016-2021
Traditional DC	46	44.9	42.1	41.4	40.8	39.1	36.2	32.9	-5%
Cloud DC	83.5	136.0	199.4	262.4	331.0	393.3	459.2	533.7	22%
Total DC	***129.5***	***180.9***	***241.5***	***303.8***	***371.8***	***432.4***	***495.4***	***566.7***	***19%***
Traditional DC	36%	25%	17%	14%	11%	9%	7%	6%	
Cloud DC	64%	75%	83%	86%	89%	91%	93%	94%	

In terms of the number of data centres, that is not a representative metric in itself, as data centres vary in size. With regards to infrastructure efficiency, indeed one metric that has been proposed to assess efficiency of data centres is Power Usage Effectiveness (PUE), which is the ration of power consumption of IT equipment (all equipment used to manage, process, store or route data in the data center) by the total power needed by the data center including infrastructure such as the power supply system, the lighting system and the cooling system. There have been studies forecasting a constant reduction in the PUE metric, meaning an optimisation of data centre efficiency based on equipment other than IT (Liu et al, 2020). Furthermore, reported trends among some of the world's largest data center operators of increasingly moving toward renewable energy procurement can also lead to a reduction of carbon emissions. (Energy Innovation, 2020)

A second factor is the change of technology towards hyperscale data centers, which are larger and more efficient. Hyperscale data centres are very efficient large-scale cloud data centres that run at high capacity, owing in part to virtualisation software that enables data centre operators to deliver greater work output with fewer servers (IEA, 2020). Furthermore, due to their efficiency and size, hyperscale data centres demonstrate low levels of PUE which in turn, lowers the energy demand of data centre infrastructure even further.

The emergence of hyperscale data centres has been credited as a main reason for the stabilisation of demand over the past half-decade. It is reported that around 400 hyperscale data centres are installed worldwide, servicing small corporations or universities that in the past would have had their own servers, and already account for 20% of the world's data-centre electricity usage (Nature, 2018).

In their estimations study for the energy use of data centers in the US, Shehabi et al (2016) identify a number of efficiency trends which explains a rather static energy consumption between 2010 and 2020:

- Average server utilization
- Server power scaling at low utilization
- Average power draw of hard disk drives
- Average power draw of network ports
- Average infrastructure efficiency (i.e., PUE)

They also present Figure 14 below, which demonstrates the static electricity use from 2010 to 2020 under current efficiency and growth rates, the trajectory of electricity use that would have materialised had there not be energy efficiency strategies, and estimations of electricity use reductions should further efficiency scenarios be implemented.

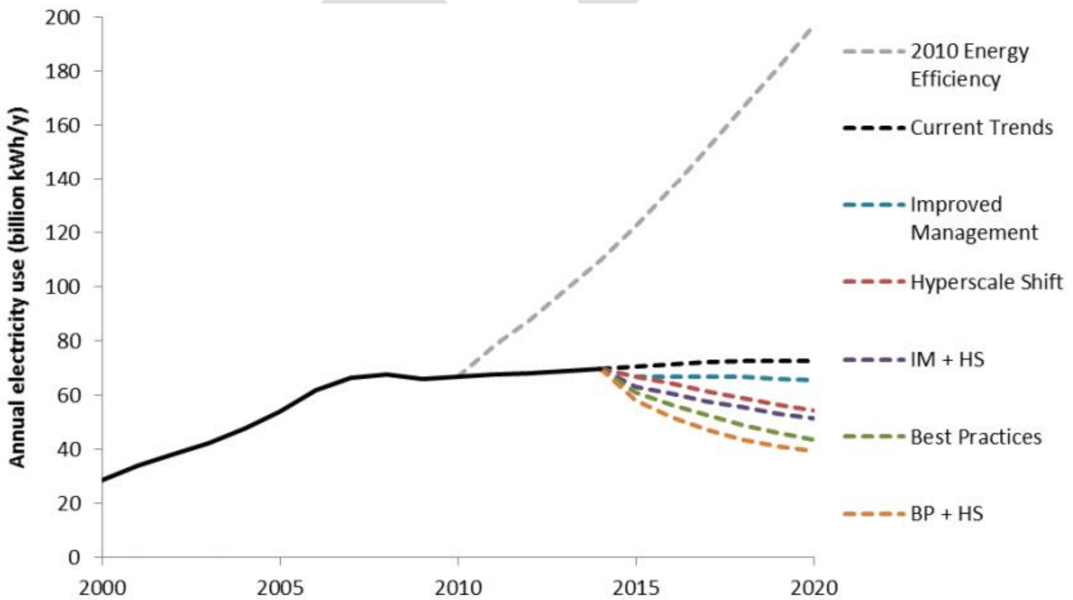


Figure 14: Effect of energy efficiency strategies on energy consumption scenarios for data centres in US. Source: Shehabi et al (2016)

The strategies range from improving the least efficient components of the data center stock ("Improved Management" scenario) and assuming an aggressive "Hyperscale Shift" of data centers to adopting the most efficient technologies ("Best Practices"), and combinations of the above scenarios Shehabi et al (2016).

The impact of both factors of increased efficiency on energy use is demonstrated in the following Table 7 (Masanet et al, 2020). The results in the table on one hand suggest an increase in the number of data centre servers, as well as an increase in the energy consumption for servers, storage and network port usage of the data centres. However, a significant reduction in energy use associated with data centre infrastructure and cooling needs brings the projection to a reduction of energy use in 2023 compared to both globally and in Western Europe.

Table 7: Efficiency trends for data centres in Western Europe according to Masanet et al, 2020.

Western Europe	**2010**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
1. Traditional data centre servers (thousands)	7386	2831	2531	2266	2026	1759	1528
2. Cloud (non-hyperscale) servers (thousands)	117	2700	2536	2510	2413	2750	3130
3. Hyperscale servers (thousands)	437	3155	3801	4292	4943	5510	6143
	7940	*8687*	*8868*	*9068*	*9382*	*10019*	*10801*
SERVERS							
1. Traditional data centre server energy use (TWh)	15.06	5.96	5.49	5.14	4.87	4.48	4.17
2. Cloud (non-hyperscale) server energy use (TWh)	1.54	6.78	6.34	6.15	5.81	6.33	6.91
3. Hyperscale server energy use (TWh)	1.02	7.06	8.45	9.46	10.79	11.89	13.12
	17.6	*19.8*	*20.3*	*20.8*	*21.5*	*22.7*	*24.2*
STORAGE							
1. Traditional data centre storage energy use (TWh)	1.51	1.00	0.76	0.58	0.53	0.52	0.51
2. Cloud (non-hyperscale) storage energy use (TWh)	0.05	1.56	1.34	1.30	1.18	1.22	1.26
3. Hyperscale storage energy use (TWh)	0.17	1.82	2.01	2.21	2.41	2.44	2.47
	1.7	*4.4*	*4.1*	*4.1*	*4.1*	*4.2*	*4.2*
NETWORK PORT USAGE							
1. Traditional data centre network port energy use (TWh)	0.47	0.17	0.14	0.12	0.11	0.10	0.08
2. Cloud (non-hyperscale) network port energy use (TWh)	0.01	0.23	0.19	0.17	0.16	0.19	0.21
3. Hyperscale network port energy use (TWh)	0.04	0.36	0.40	0.41	0.48	0.54	0.61
	0.5	*0.8*	*0.7*	*0.7*	*0.7*	*0.8*	*0.9*
PUE							
1. Traditional data centre PUE	2.23	2.06	1.99	1.93	1.87	1.81	1.76
3. Cloud (non-hyperscale) data centre PUE	1.75	1.62	1.58	1.55	1.52	1.49	1.46
4. Hyperscale data centre PUE	1.23	1.18	1.17	1.17	1.16	1.16	1.15
COOLING etc.							
1. Traditional data centre infrastructure energy use (TWh)	20.93	7.53	6.32	5.43	4.80	4.13	3.62
2. Cloud (non-hyperscale) infrastructure energy use (TWh)	1.20	5.29	4.56	4.19	3.72	3.79	3.86
3. Hyperscale infrastructure energy use (TWh)	0.28	1.67	1.90	2.04	2.23	2.34	2.46
	22.4	*14.5*	*12.8*	*11.7*	*10.7*	*10.3*	*9.9*
TOTAL ENERGY USE (TWh)	***42.3***	***39.4***	***37.9***	***37.2***	***37.1***	***38.0***	***39.3***
EU27 (Western Europe x 1.06)	*44.8*	*41.8*	*40.2*	*39.4*	*39.3*	*40.3*	*41.7*

The above efficiency trends illustrate one side of the coin. Firstly, metrics such as PUE may give misleading signals, due to their focus on efficiency improvements for non-IT equipment (VHK and Viegand Maagøe, 2020). Indeed, pressures on IT equipment and related to aforementioned data demand growth trends would not be reflected. It can therefore be argued that for the purposes of this study, this metric should be considered with caution. In fact, despite the overall reduction in the period 2010-2023, the table above still predicts an increase as from 2021. This increase is in line with estimations looking at the electricity usage of data centres from a top-down approach and with a wider future horizon. The Figure 15 below from Andrae and Endler (2015) indeed demonstrates a more alarming trend.

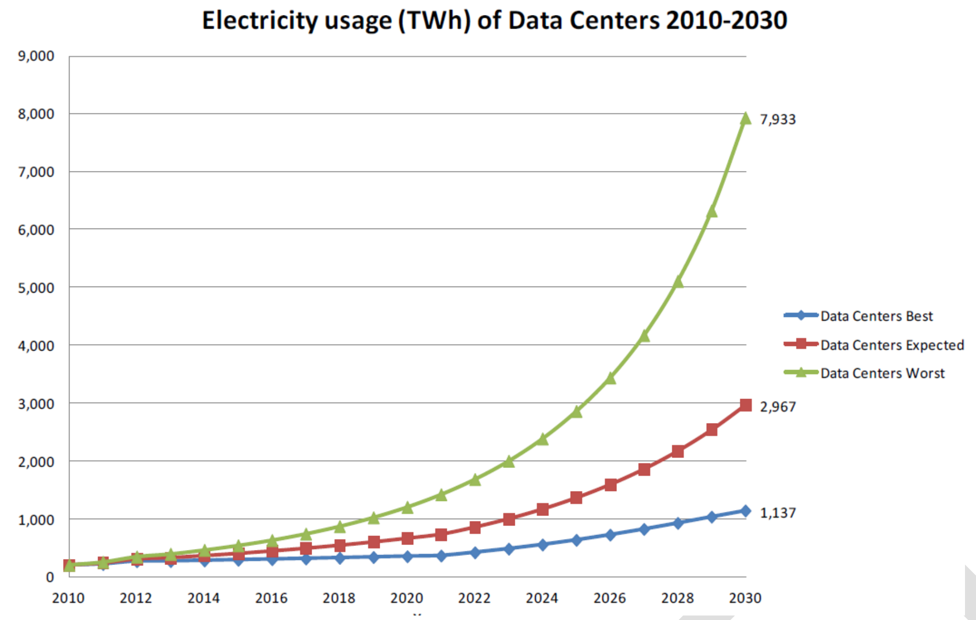


Figure 15: Electricity usage (TWh) of Data Centres (2010-2030) according to Andrae and Endler (2015)

Looking closely into the elements that contribute to shaping energy use trends might provide additional insights, with main energy consumption increase factors being increased data demand and installed storage capacity, examined below in Figure 16. (Statista, 2021).

Figure 16: Trends in the installed storage capacity in exabytes (10^{18} bytes). Source: Statista, 2021

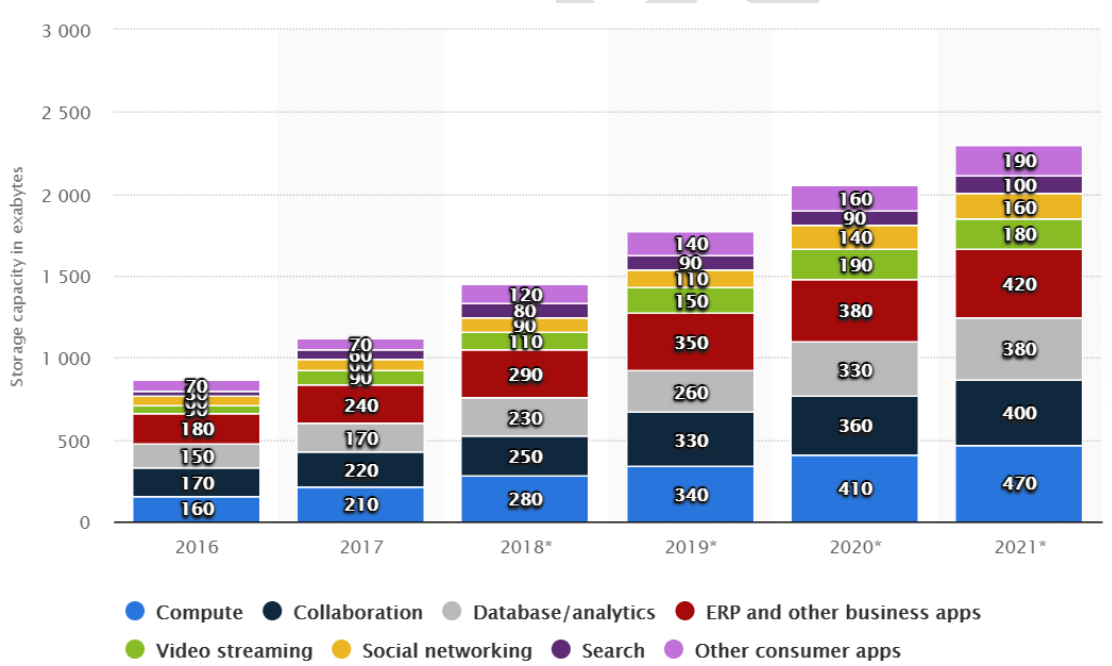


Table 8 below originating from Cisco 2016 (via VHK and Viegand Maagøe, 2020), demonstrates the increase in data centre traffic in the last years, predicting further increase.

Table 8: Trends in Global data Centre Traffic. Source: Cisco 2016 (via VHK and Viegand Maagøe, 2020)

	2016	2017	2018	2019	2020	2021	CAGR 2016-2021
	By type (EB per year)						
DC to user	998	1280	1609	2017	2500	3064	25.2%
DC to DC	679	976	1347	1746	2245	2796	32.7%
within DC	5143	6831	8601	10362	12371	14695	23.4%
	By segment (EB per year)						
Consumer	4501	6156	8052	10054	12401	15107	27.4%
Business	2319	2931	3505	4070	4716	5449	18.6%
	By type (EB per year)						
Cloud DC	5991	8190	10606	13127	16086	19509	26.6%
traditional DC	828	897	952	997	1030	1046	4.8%
Total DC	6819	9087	11557	14124	17116	20555	24.7%

IEA (2020) also expect the continuation of this exponential growth, with global internet traffic expected to double by 2022 to 4.2 zettabytes per year (4.2 trillion gigabytes).

This trend is attributed to the number of mobile internet users projected to increase from 3.8 billion in 2019 to 5 billion by 2025, and the number of Internet of Things (IoT) connections is expected to double from 12 billion to 25 billion (see also section 3.5 below). This increased traffic, and especially in mobile networks, may be a cause of concern from an energy efficiency perspective as mobile networks are more energy-intensive (even more so in video streaming) and also growth in traffic in "busy hour" may lead service provides to see network capacity increases (Morley et al, 2018; Cisco 2017)

These increase trends may have been exacerbated by the unforeseen even of the Covid-19 pandemic. IEA (2020) report that global internet traffic surged by almost 40% between February and mid-April 2020, driven by growth in video streaming, video conferencing, online gaming, and social networking.

3.3.1 Edge network and computing

Another area worthy of focus is the emergence of the edge network and computing, which, as a response to increasing digitalisation and data demand growth, decreases data processing costs and latency by bringing "high-performance compute, storage, and networking resources closer to users and devices" Montevecchi et al (2020). The figure below presents the range of applications where edge computing is used (Cisco, 2020)

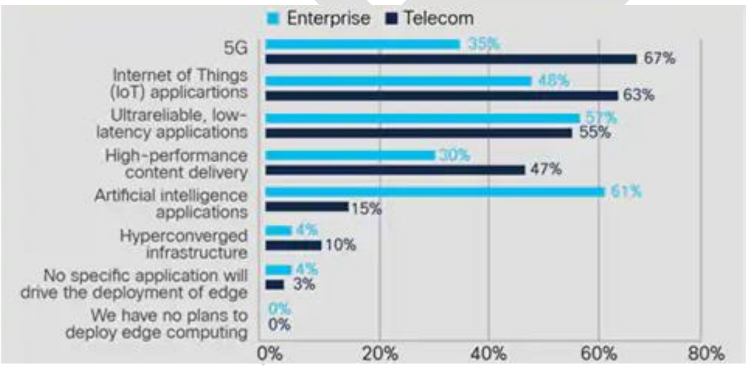


Figure 17: Edge Computing use cases. Source: (Cisco, 2020).

Edge data centres may operate less efficiently than large cloud data centres due to their size and architecture. Even though edge computer currently plays a minor role in energy consumption of data centres, Montevecchi et al (2020) forecast that edge data centres will account for around 10% of the server capacity installed in the EU28 in 2025, and therefore account for 12% of the energy demand of all data centres in the EU28. For the year 2030, it is assumed that edge data centres will account for 40% of the total server capacity (Figure 18). With the expansion of 5G mobile networks and hightech developments such as industry 4.0 and autonomous driving, the demand for small decentralised edge computing centres could see a massive increase. In this case, the energy consumption of all data centres in the EU28 could rise to approx. 120 TWh/a.

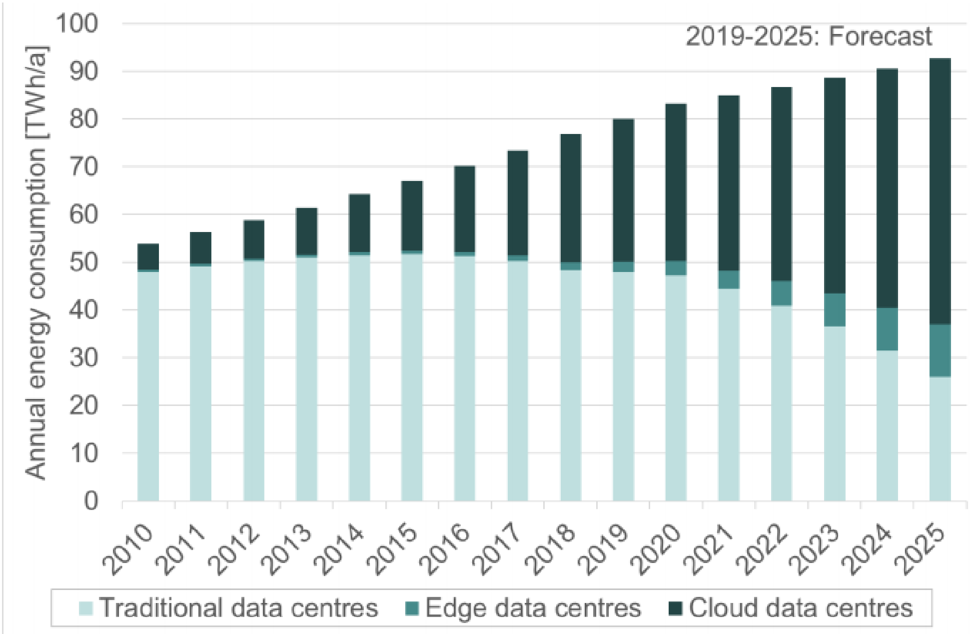
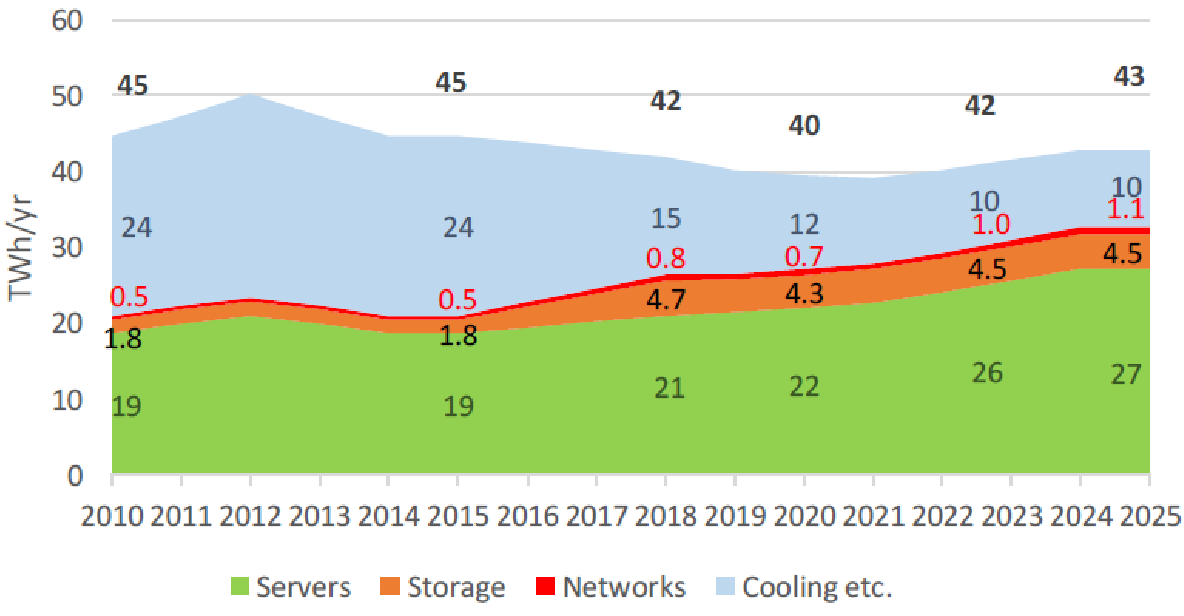


Figure 18: Trends and forecasts in terms of energy consumption by data centre type in EU28. Source: Montevecchi et al (2020)

Overall, VHK and Viegand Maagøe (2020) conclude that the growth and efficiency effects for data centres cancel each other out leading to energy use remaining stable until 2025 (see Figure 19).

Figure 19: Trends and forecasts for the data centres electricity use in EU27 (in TWh/yr). Source: VHK and Viegand Maagøe, 2020



3.4 Network Infrastructure

Similar trends of technological improvements leading to increased efficiency and data demand growth are seen in network infrastructure equipment as well.

IEA 2020 reports that energy efficiency of data transmission networks is improving rapidly, with fixed-line network energy intensity having halved every two years since 2000 in developed countries, and mobile-access network energy efficiency having improved by 10-30% annually in recent years.

At the same time, the same source expects data network consumption to rise to around 270 TWh in 2022 from around 250 TWh in 2019.

According to Andrae and Edler 2015 models, consumption is expected to increase further in the next years leading to 2030 in fixed access networks, both wired (Figure 20) and wi-fi (Figure 21), both attributed to growth in data traffic.

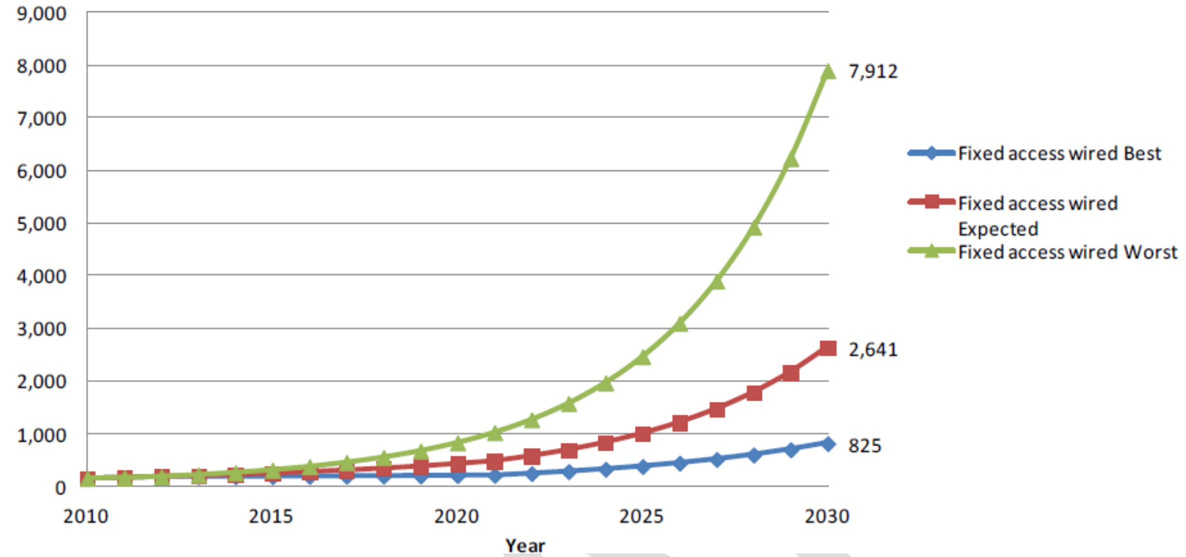


Figure 20: Electricity Usage (TWh) of Fixed access wired networks 2010 – 2030 according to Andrae and Edler 2015

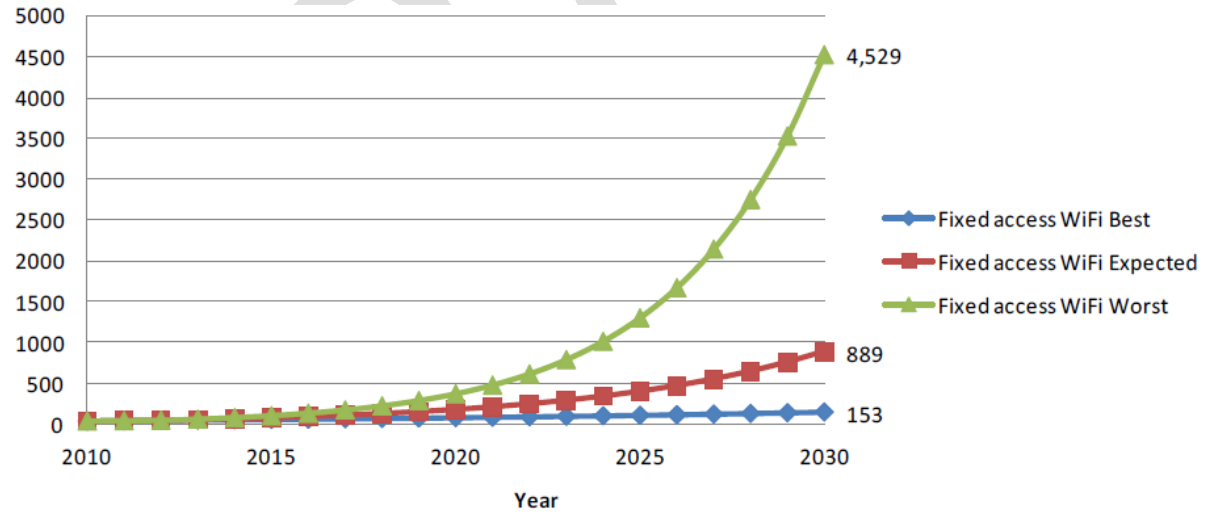


Figure 21: Electricity Usage (TWh) of Fixed access Wi-Fi networks 2010 – 2030 according to Andrae and Edler 2015

Network speed is another driver of internet traffic. According to Cisco (2020), anecdotal evidence supports the idea that overall use increases when speed increases, and broadband-speed improvements result in increased consumption and use of high-bandwidth content and applications. Table 9 and Table 10 below demonstrate the increase in fixed and mobile network speeds (in Mbps) both in Europe and globally almost, or in some cases above, threefold.

Table 9: Fixed broadband speed (on Mbps), 2018-2023

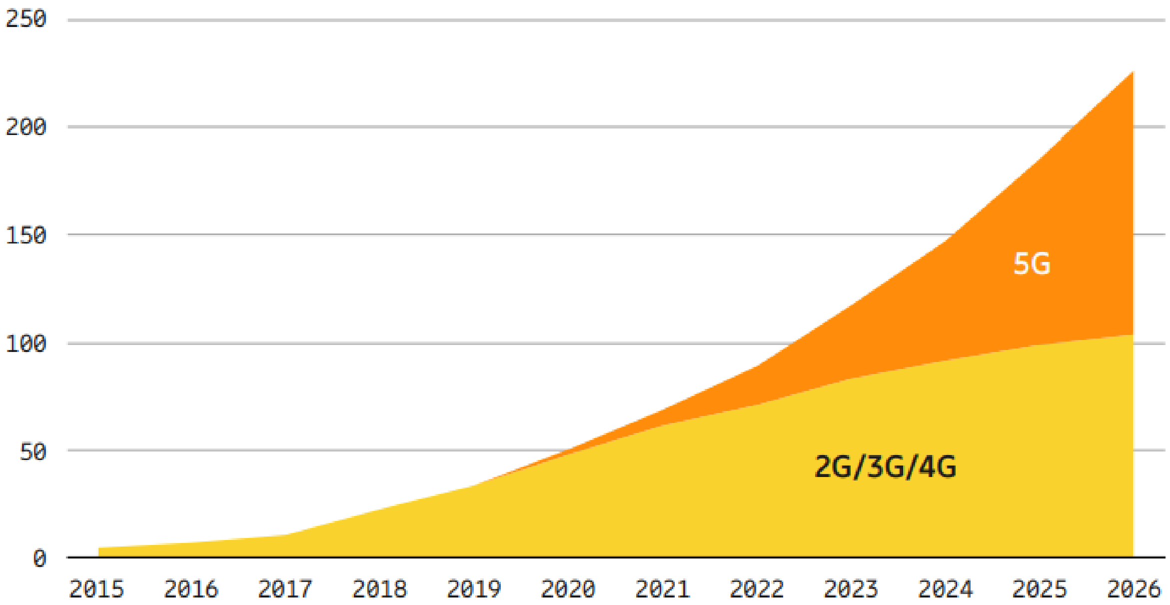
Region	2018	2019	2020	2021	2022	2023	CAGR (2018–2023)
Global	45.9	52.9	61.2	77.4	97.8	110.4	20%
Asia Pacific	62.8	74.9	91.8	117.1	137.4	157.1	20%
Latin America	15.7	19.7	34.5	41.2	51.5	59.3	30%
North America	56.6	70.1	92.7	106.8	126.0	141.8	20%
Western Europe	45.6	53.2	72.3	87.4	105.6	123.0	22%
Central and Eastern Europe	35.0	37.2	57.0	65.5	77.8	87.7	20%
Middle East and Africa	9.7	11.7	25.0	29.0	34.9	41.2	33%

Table 10: Average mobile network connection speeds (in Mbps) by region and country

Region	2018	2019	2020	2021	2022	2023	CAGR (2018–2023)
Global speed: All handsets	13.2	17.7	23.5	29.4	35.9	43.9	27%
Asia Pacific	14.3	18.0	24.7	32.4	39.0	45.7	26%
Latin America	8.0	11.2	15.7	21.1	24.8	28.8	29%
North America	21.6	27.0	34.9	42.4	50.6	58.4	22%
Western Europe	23.6	31.2	40.1	48.2	54.4	62.4	21%
Central and Eastern Europe	12.9	15.7	21.3	30.3	36.1	43.0	27%
Middle East and Africa	6.9	9.4	13.3	17.6	20.3	24.8	29%

Another factor of future IP traffic increase is the evolution of mobile devices from lower-generation network connectivity (2G) to higher-generation network connectivity such as 3G, 3.5G, 4G or LTE and now also 5G). More capable device and faster, more intelligent networks will facilitate the adoption of advanced multimedia applications that contribute to increased mobile and Wi-Fi traffic. Cisco 2020

Ericsson (2020) reports that 5G is estimated to cover around 60% of the population in 2026 compared to 15% in 2020, a trend exacerbated by COVID-19, making it the fastest deployed mobile communication technology in history. As shown in Figure 22, the same study predicts that in 2026, 5G networks will carry more than half of the world's mobile data traffic.



Note: This graph does not include traffic generated by fixed wireless access (FWA) services.

Figure 22: Trends and forecasts for global mobile data traffic (Exabites for months). Source: Ericsson (2020)

With such increase in traffic, what is the impact on energy consumption? Again studies focus on the question of whether energy efficiency potential of the new 5G protocol can compensate for the increased traffic generated.

In terms of efficiency, reports agree that the 5G protocol has the potential to achieve higher energy efficiency than legacy protocols. A new study by Nokia and Telefónica (Nokia, 2020) has found that 5G networks are up to 90 percent more energy efficient per traffic unit than legacy 4G networks, with more data bits per kilowatt of energy than any previous wireless technology generation. Montevecchi et al (2020) point out that 5G brings promising opportunities through new technologies that improve energy-efficiency. On the one hand within the RAN, the data volume transferred per energy consumed can be improved through high data transmission rates, which allow more data to be transmitted from a single transmitter with comparable power consumption. On the other hand, 5G brings other possibilities like small cell offloading and mobile edge caching (Yan et al., 2019) that can reduce the overall energy consumption of cloud application. Manufacturer of mobile network equipment aim to reduce the energy intensity of mobile data transmission (kWh/GB) by the factor 10 until 2022 compared to 2017.

However, for those efficiency levels to be realised, actions are necessary. According to Emil Björnson, an associate professor at Linköping University, (Clari et al) two fundamental aspects of 5G are an increase in the number of small cells and the rise of massive multiple-input multiple-output (MIMO) antennas. The increased number of small cells will logically imply higher energy consumption, but it has been pointed out that the individual energy consumption of each small cell is much lower than in a conventional cell. Concerning massive MIMO, it involves the use of arrays with many more antennas at each base station, which requires many more hardware components per base station and therefore more energy. A white paper released by Nokia (2016) base stations should be the subject of focus as they consume 80% of the energy used (only 15% of the energy is used to forward bits). Most of the energy is used for system broadcasts and running idle resources, to power fans and cooling systems (over 50% of the energy consumption), for heating and lighting, and to run uninterruptible and other power supplies. However, as the MIMO technology develops, its energy efficiency may also improve over time: the MAMMOET project has predicted that future massive MIMO base stations will consume less energy than 4G base stations, despite the fact that they will contain more hardware. A second solution is the possibility to put the base stations in "sleep mode" when there are no active users is one of the main ways to reduce energy consumption. Indeed, it is expected to reduce energy consumption by almost 10 times compared to current systems.

Montevecchi et al (2020) find that despite the optimism about the services and the interplay with edge computing enabled by 5G, there are significant concerns about rising costs. The move to 5G is likely to increase total network energy consumption by 150 to 170 % by 2026. Looking at the total energy consumption of mobile networks, these efficiency gains can be reduced or even erased by heavily increasing data transmission through the mobile networks. Increasing data volumes and the development of 5G mobile networks are also likely to boost the demand for decentralised computing capacities in edge data centres.

3.5 Consumer Devices

As referenced above, the trend in electricity consumption in ICT systems will see consumption moving from the end-user devices to the network and data centre infrastructure. Looking at consumer devices independently from the ICT system and from a top-down approach, it is estimated by Andrae and Edler 2015 that the electricity usage that can be attributed directly to consumer devices will trend towards reduction onto 2030.

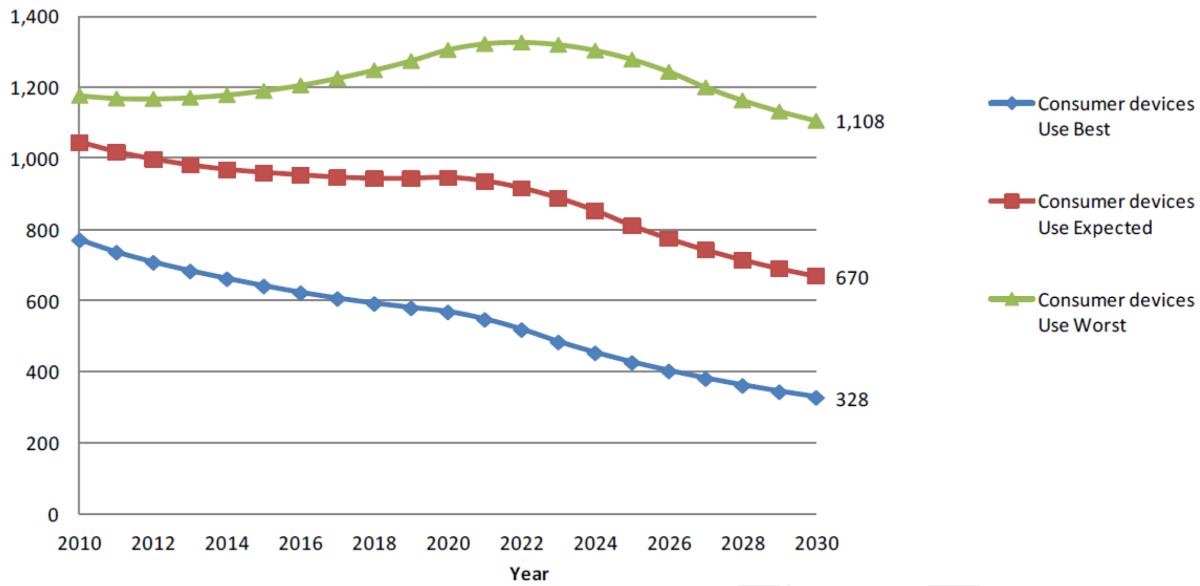


Figure 23: Electricity usage (TWh) of Consumer Devices 2010 – 2030. Source: Andrae and Edler 2015

However, as it becomes evident by the methodological challenges presented in section 3.1, such reduction alone does not mean devices do not contribute to increasing energy consumption of ICT systems as a whole. Therefore, trends in consumer device use could still offer insight into the increasing energy use associated with the mobile access network presented above.

Projections from Cisco (2020) demonstrate an increase in the number of internet users, mobile users, networked device connections by 2023 compared to 2018 in both "Western Europe" and "Central and Eastern Europe" regions (see Table 11).

Table 11: Internet users, mobile users, networked device connections in the period 2018-2023 in different European Regions. Source: Cisco (2020).

	Western Europe		Central and Eastern Europe	
	2018	2023	2018	2023
Internet users	345 million	370 million	323 million	388 million
Mobile users	357 million	365 million	394 million	404 million
Networked devices/connections	2.4 billion	4.0 billion	1.2 billion	2.0 billion

The number of devices themselves are also growing globally, with this trend mainly driven by the growing number of Machine-to-Machine (M2M) applications, such as smart meters, video surveillance, healthcare monitoring, transportation, and package or asset tracking, are contributing in a major way to the growth of devices and connections. Second most-growing type of devices are smartphones, followed by connected TVs. (Cisco, 2020)

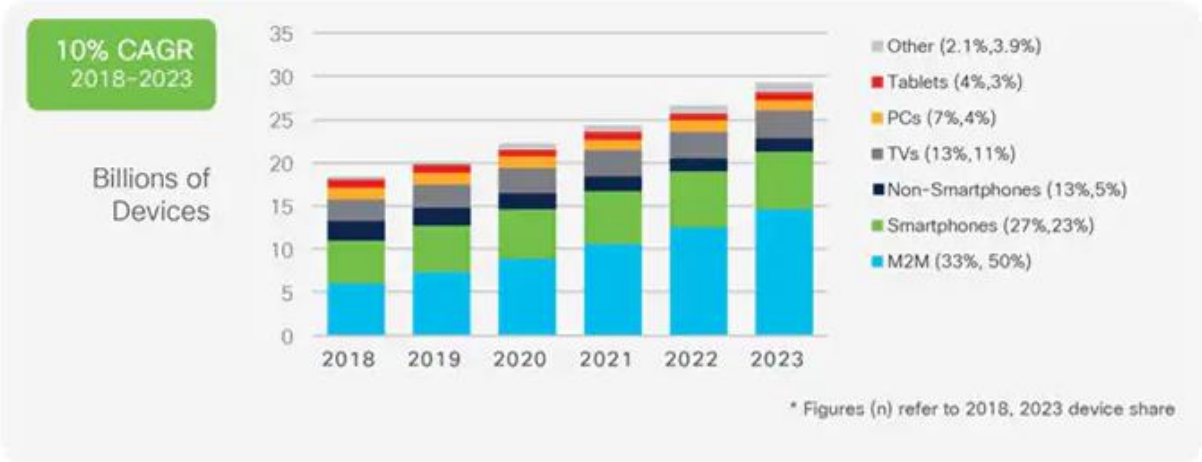


Figure 24: Number of connected devices in billions. Source: Cisco (2020)

M2M applications (i.e. the main driver of growth of IoT devices) are expected to grow to such an extent that IoT devices will account for 50 percent (14.7 billion) of all global networked devices by 2023 (Figure 25). Trends in the area of IoT and M2M may provide indications and explanations for the rise in network access connections presented above. (Cisco, 2020)

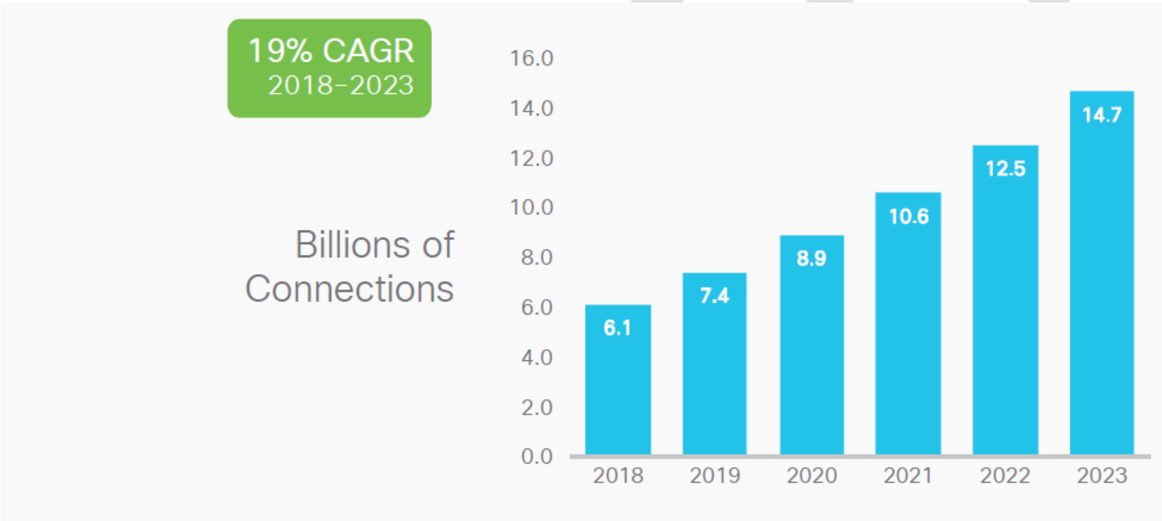


Figure 25: Global M2M Connection Growth. Source: Cisco (2020).

The Internet of Things (IoT) has been defined in Recommendation ITU-T Y.2060 (06/2012) as a global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies. (ITU, 2012)

As the following figure demonstrates, the energy consumption enabled by the semiconductors (here integrated circuit chips, i.e. sensors, processor integrated circuits (ICs), and connectivity ICs) themselves used in IoT devices is expected to reduce to insignificant levels (see Figure 26) (Das and Mao, 2020).

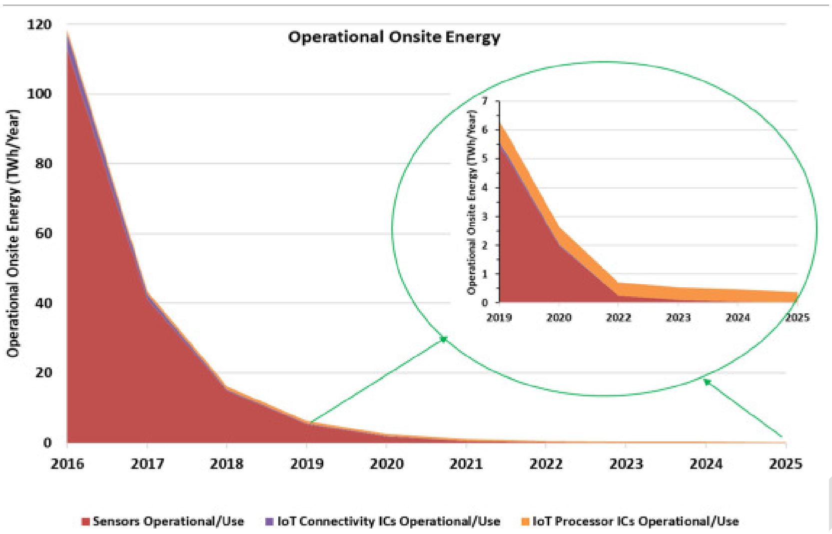


Figure 26: Projection of the operational energy consumption of semiconductors in the IoT (sensors, connectivity ICs, Processors ICs). Source: (Das and Mao, 2020)

What is more relevant is the effect that IoT technologies can have on the energy consumption of ICT systems via second-order effects (see project's Task 2). On one hand, smart functionalities can allow devices to operate in ways that save energy via optimization effects, and on the other, enable energy consumption of ICT systems via a large amount of data transfer and remote processing, i.e. induction effects. Optimization effects are studied in part 3a.

The applications that currently drive internet traffic growth are video streaming, social networking and gaming (Figure 27). Video streaming in particular not only holds the lion's share of internet traffic with 57.6% of share in year 2020, but also demonstrates the highest percentage of increase, having grown its share by 2.2% compared to the year before. Social networking applications are responsible for 10.7% of internet traffic, an increase of 1.78% compared to 2019. Finally, even though still in 7th place, gaming poses as a main driver for internet traffic in the future with 4.2% of the share, which has almost doubled since 2019 (Sandvine, 2020).

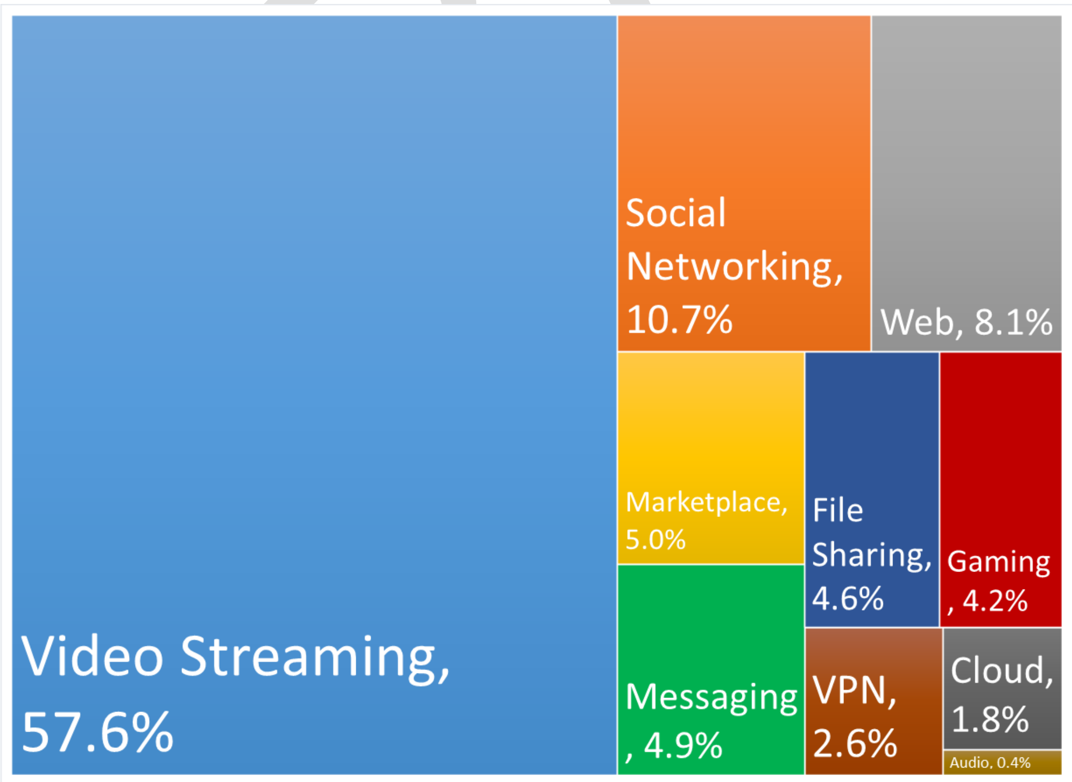


Figure 27: Global Application Category Total Traffic Share [data from Sandvine 2020]

Video streaming involves the operation of many parts of an ICT system. A video is projected in a device, but it is stored in a data center facility. The streaming is achieved via the internet which is provided by a network infrastructure. Figure 28 demonstrates the ICT system devices and processes used to provide a streaming video service to a viewer (Shehabi et al 2014).

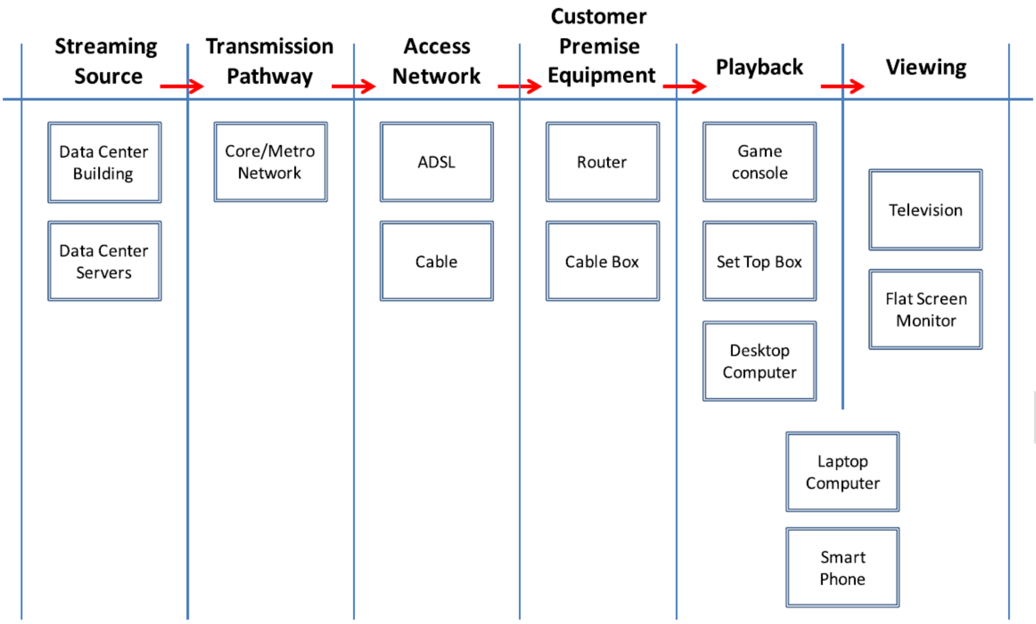


Figure 28: ICT system devices and processes used to provide a streaming video service to a viewer. Source: Shehabi et al 2014.

Video traffic over mobile networks alone is growing by 55% per year (Cisco, 2020).

Therefore, as noted in section 3.1, allocating the energy consumption (and overall environmental impact) of video streaming and other application categories to one part of the system alone, or investigating only the energy consumption of end use devices, poses the risk of not only a misrepresentation of energy use reality, but also an inability to identify future trends.

Coroama and Hilty (2014) conclude that in order to determine the energy consumption caused by streaming and watching a video from the Internet, the system under study should include and separately consider:

(a) a properly allocated share of the consumption of the server providing the video (energy per time, i.e. just power)

(b) the consumption caused in the Internet by transmitting the data

(c) the end-user device's electricity consumption for the duration of the video being watched, *(measure energy intensity in energy per data)*

They further deem arguable whether devices should be considered relevant when defining the system boundary for the energy intensity of the Internet, because on one hand different types of devices have different energy consumption levels, and also consumption would be dependent on the applications used in those devices. However, they do argue in favour of considering customer premises equipment (CPE), which are mainly WiFi routers and modems.

Data from the previous section do not bring us to a conclusive answer to the question of the future of data centre energy use. Beyond methodological divergence, there is again the challenge of scope. Indeed, Bashroush (2020) maintains that bottom-up studies projecting energy efficiency gains enough to maintain a static energy consumption suffer from methodological uncertainty, and may potentially have excluded from the scope energy use associated with small to medium data centres, bitcoin mining and edge computing demands. Further trends supporting this challenge are the large increase in video streaming demand and mobile traffic, and the levels of electricity consumption increases report by some of the biggest streaming services. According to Google's published data, their electricity consumption went up by 33% between 2017 and 2018 (Google, 2019). Similarly, Netflix energy consumption (direct and indirect) went up by 84% between 2018 and 2019 (Netflix, 2019; Netflix, 2020). Several studies (Schien et al., 2013; Shehabi et al., 2014) argue that estimated the energy demand of digital media including video streaming is very much dependent on the end device and the access network. More specifically, Kamiya (2020) concludes that viewing devices account for the majority of energy use (72%), followed by data transmission (23%) and data centres (5%). Although the different approaches and methodologies between studies has to again be highlighted when reading those results.

Video streaming from the internet can have a substantial effect on traffic. One contributing factor is the resolution used for the streaming. The potential for traffic increase due to resolution increase can be demonstrated by Figure 29 below, whereby Cisco (2020) estimate that by 2023, two-thirds (66 percent) of the installed flat-panel TV sets will be UHD, up from 33 percent in 2018. The same source indicates that the bit rate for a UHD, or 4K, video is about 15 to 18 Mbps, meaning more than double the HD video bit rate and nine times more than Standard-Definition (SD) video bit rate (Cisco, 2020).

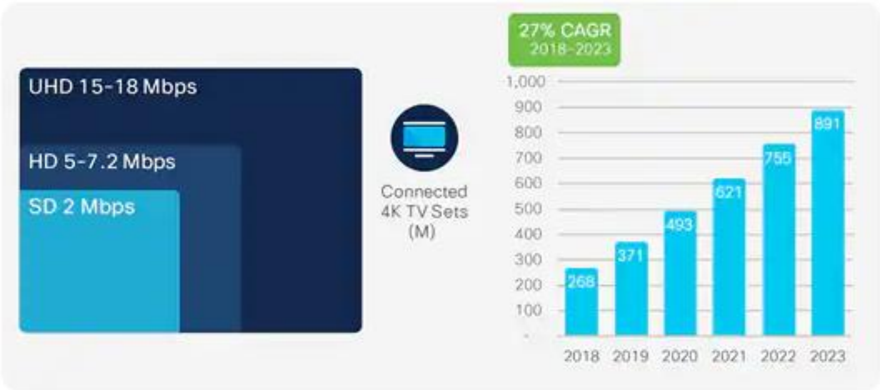


Figure 29: Increasing video definition. By 2023, 66% of connected flat panel TV sets will be 4K. Source: Cisco 2020

A characteristic example of the impact that video resolution has on internet traffic is the fact that at the early stages of the Covid-19 pandemic in Europe in March 2020, and after discussions with the European Commission, Netflix announced to reduce bit rates across all streams in Europe for 30 days, (thus reducing Netflix traffic on European networks by 25 percent), while YouTube committed to temporarily switch all traffic in the EU to Standard Definition by default (European Commission, 2020a)[5]. Sandvine (2020) predicts that if this change had not been made, video might have even touched 70% of overall bandwidth, having a mighty impact on many networks.

Another determining factor for the contribution of video streaming to traffic is the type of device used. Schien et al., 2013 attempt to bring the factors of type of device and type of network connection and Energy Consumption during the Use Stage of Online Multimedia Services (Figure 30).

[5] YouTube and Netflix are the two applications with the largest traffic share at 15.94% and 11.42% respectively (Sandvine, 2020)

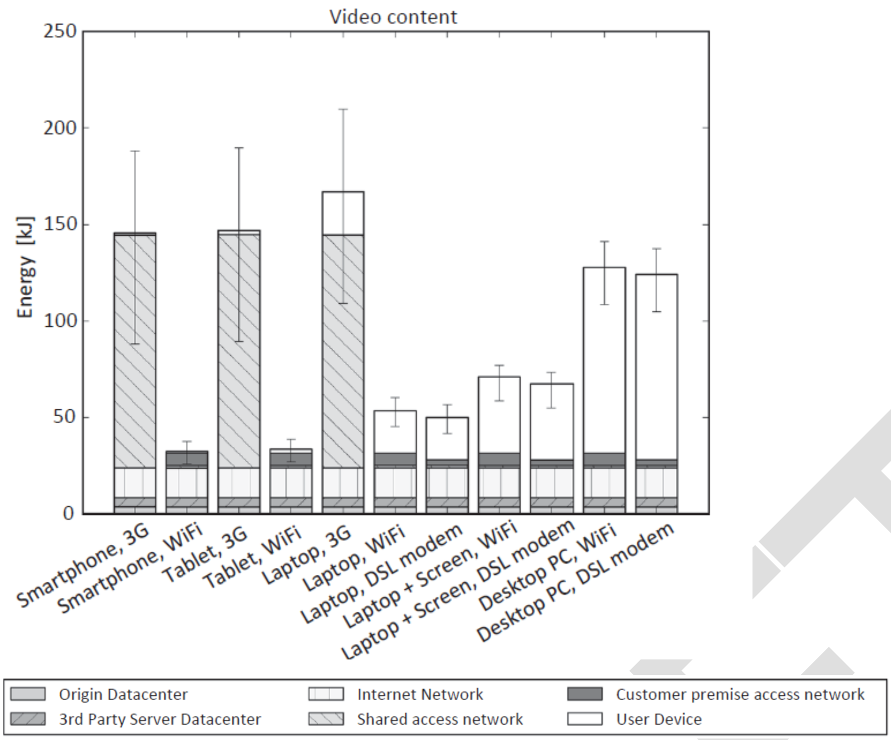


Figure 30: Energy consumption from video streaming in different configurations of access network and user device.

The graph above clear demonstrates that mobile network connectivity plays a considerable role in higher energy consumption. Combined with the rapid increase of mobile connectivity presented in the following section, this could be another area for caution in terms of energy consumption.

One device not considered in the study above is TVs whose increase connectivity combined with a higher energy consumption compared to other devices [Malmodin, 2014]. This observation plays an important role if one considers the future trends of device use for video streaming. In 2018, Netflix said that 70% of its streams end up on connected TVs instead of phones, tablets or PCs (Recode, 2018). Similarly, in 2017, YouTube reports that viewing on actual TV sets is up 70% in the last year (Recode, 2017).

Finally, Suski et al (2020) identify viewing duration of online video as another factor for the increase of online video traffic, due to user-behavioural rather than technical characteristics, such as the rise of mobile internet which can enable the parallelization of activities such as watching online video while commuting or waiting and 'All-you-can-stream' flat rates.

Gaming is another area which is also expected to constitute a major driver of future IP traffic growth, driven by the development of cloud gaming. As is the case with video streaming, cloud games transfer graphics processing, and therefore energy consumption needs, to data centres and the ICT system.

A 2019 study (Mills et al, 2019) concludes that cloud-based gaming requires significantly more energy than similarly powerful equipment located in the gamer's home. Further investigation into two scenarios for cloud gaming in the United States - one assuming only 20% of cloud gaming by 2021 and another 75% - reveals higher energy use by 17% in the second scenario in the five years between 2016 and 2021.

A similar study (Marsden et al 2020) with a wider focus on carbon emissions examined three scenarios - one where streaming remains niche, a scenario where 30% of gaming moves away from conventional and into streaming platforms, and one assuming 90% of gaming switches to streaming over the next decade. It is estimated that emissions would be 30% higher per year from 2030 in the high-streaming scenario compared to a low-streaming one (Figure 31).

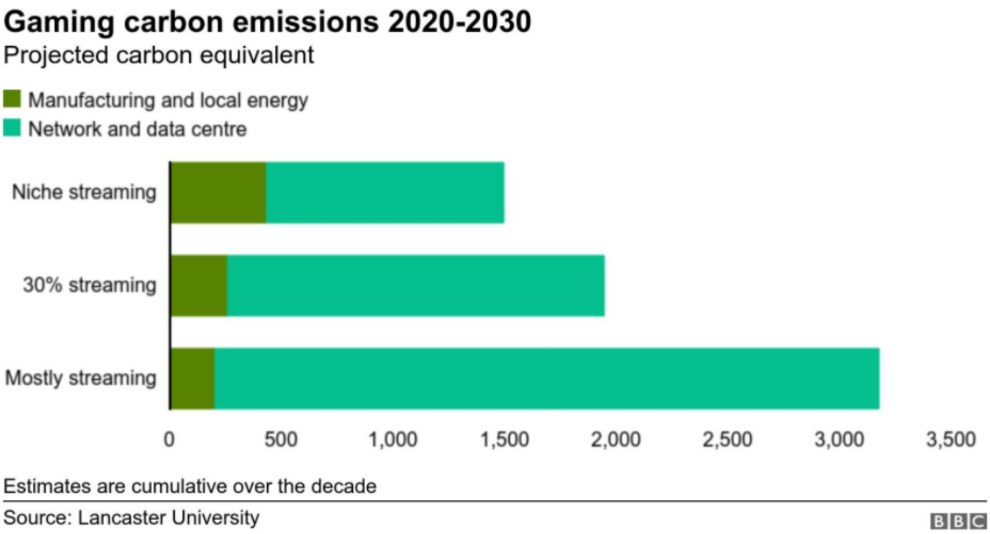


Figure 31: Cloud gaming: Are game streaming services bad for the planet? Figure source: BBC (2020). https://www.bbc.com/news/technology-53838645

Another area of interest that can affect the energy consumption of ICT systems is the mining of Bitcoin and other cryptocurrencies.

A summary of studies (Koomey, 2019) suggests that Bitcoing electricity consumption accounts for 44 TWh annually, or about 0.2% of global electricity use. That number seems to be in agreement with another study of the same year by Stoll et al (2019) who suggest a consumption of 45.8 TWh of electricity per year as of November 2018, accounting again for about 0.2% of global electricity consumption.

However, it has to be noted that those results are associated with a high level of uncertainty. IEA (2019b) notes that bitcoin's electricity consumption are wide-ranging, presenting results from a number of studies which range from 20-80 TWh annually, or about 0.1-0.3% of global electricity use. Another study by de Vries (2019) raises the number of energy consumption from mining operations to 0.5% of worldwide electricity use by the end of 2018—and eventually as much as 5%.

Such wide divergence derives from the fact that bitcoin and other cryptocurrencies exhibit rapid rates of change, even faster than growth in normal IT. This rapidity is driven in part by the volatile nature of cryptocurrency prices (Koomey, 2019). Furthermore, details about mining facilities, the hardware, and software use, are scarcely revealed, making estimations difficult.

And all that without account for other cryptocurrencies beyond Bitcoin.

3.6 Conclusions

The question is a matter of new energy efficient technologies driving energy consumption reduction, and data traffic increases driving consumption up. The main drivers of higher energy efficiency include the shift to larger and more efficient hyperscale data centres, as well as technological improvements in terms of computation and network devices. On the other hand, exponential increases expected in terms of the number of devices, connections, subscriptions, streaming and, subsequently, data demand and IP traffic, may deem efficiency improvements insufficient to curb the consumption trajectory. Indeed, several studies (especially ones using a top-down approach) conclude that energy consumption of ICT systems will increase, while more optimistic studies (especially those using a bottom-up approach) argue that it will remain more or less the same due to higher efficiency. Due to fast tech cycles, these estimations are associated with some level of uncertainty, especially when it comes to the impact of technologies and applications such as bitcoin mining, video streaming resolutions etc.

4 Qualitative contribution of ICT to energy efficiency in systems ("Internet of Things")

4.1 IoT market penetration and effects

The importance of Internet of Things (IoT) is demonstrated by its projected increasing use in the following years, as depicted in Figure 25 above.

The first order effects deriving from IoT deployment (i.e. contribution to energy consumption) are described in 3b. In this section 4, second order effects associated with the use of IoT and digitalisation are presented, namely in terms of system optimisation and increase of system efficiency. This efficiency is achieved in various sectors where IoT is utilised, ranging from the energy system to buildings and from industrial applications to transport. It also materialises with the use of various technologies, from sensors and connection protocols to energy meters and data analysis.

4.2 IoT Applications

4.2.1 Application Taxonomy

Shaikh et al(2017) offer a useful taxonomy of Green IoT applications in Figure 34. Green IoT can be defined as "the energy efficient procedures (hardware or software) adopted by IoT either to facilitate reducing the greenhouse effect of existing applications and services or to reduce the impact of greenhouse effect of IoT itself".

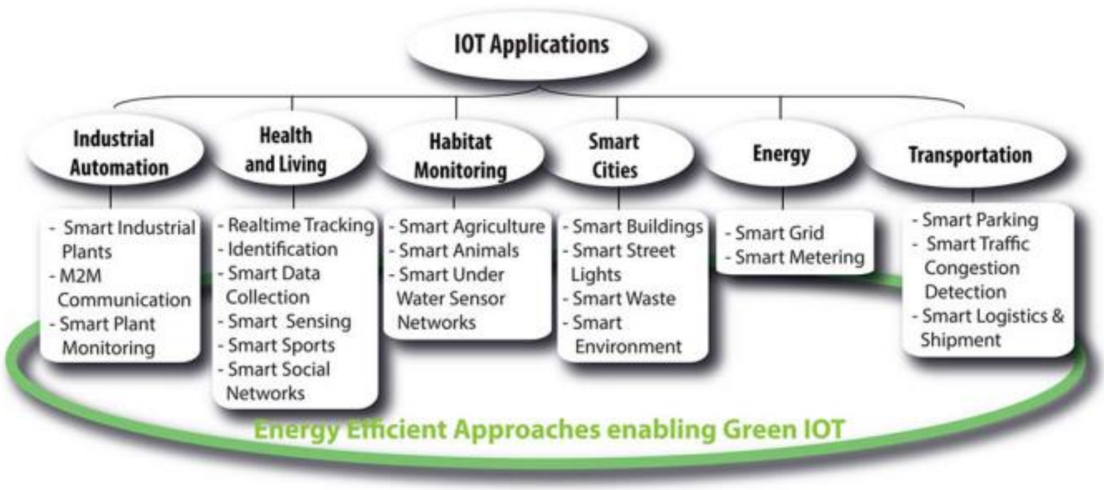


Figure 32: Energy efficiency approaches enabling Green IoT

1. Industrial Automation, including applications such as smart industrial plants and M2M communication, which help improve automation of industrial plants and improve energy efficiency by monitoring various parameters, such as temperature, air pollution and machine faults.
2. Health and Living, whereby applications such as smart data collection in the healthcare sector can achieve energy efficiency by reduction of processing time, automated hospital admission processing, and automated care and procedure auditing.
3. Habitat Monitoring, and smart agriculture with the deployment of smart underground sensors and smart insect detection and monitoring of irrigation systems and environmental impacts.
4. Smart Cities, encompassing a wide range of applications within urban spaces such as smart buildings Smart homes and offices use IoT devices to optimize HVAC or lighting management, but also support energy demand and renewables integration (Hittinger and Jaramillo 2019). In street

lighting,conventional street lighting systems which remain turned on until morning, and often in areas without presence of people can be replaced by energy efficient monitoring systems. Digital technologies can also enable smart waste management systems, by improving recycling, facilitating the use of recyclates by producers, enabling better purchasing and sorting decisions by consumers, and improving waste sourcing options for recyclers (EEA, 2021).

5. Energy system applications, such as smart metering. Smart meters enable two-way communication between the smart meter and the utility company by recording the consumption of electric energy and transmitting that information for billing purposes.

6. Transportation, including solutions such as Smart Parking, Smart Traffic Congestion Detection and Smart Logistics/Shipment applications which can reduce traffic congestion, help enterprises to respond to changing markets in the shortest possible time and improve the efficiency of the food supply chain.

Figure 33 from Horner et al 2016 provides examples of impacts from ICT services which are related to the positive effects of substitution and optimisation ("efficiency").

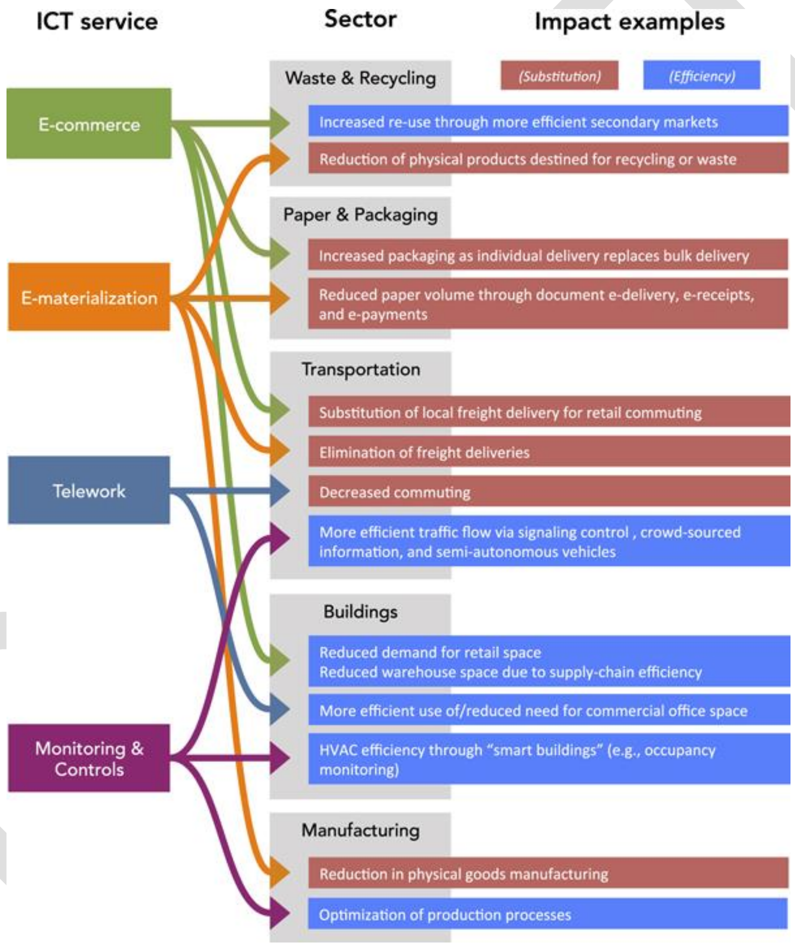


Figure 33: Impact of ICT Services in different sectors

The impacts span across many sectors, and also refer to impacts which may go beyond those considered as second-order effects and within those considered third-order effects (e.g. impacts on transportation, reduced demand/need for building space). For the purpose of this study, our focus is on the effects on the Manufacturing, Energy and Buildings sectors.

4.2.2 Industry / Production Management

Digital technologies are changing the face of industry and the way we do business. They create new business models, allow industry to be more productive, provide workers with new skills and support the decarbonisation of our economy. The digital sector will also contribute to the European Green Deal, both as a source of clean technology solutions and by reducing its own carbon footprint (European Commission, 2020b).

In industry, many companies have a long history of using digital technologies to improve safety and increase production. Further cost-effective energy savings can be achieved through advanced process controls, and by coupling smart sensors and data analytics to predict equipment failure (IEA 2019a).

IoT technologies provide awareness of energy consumption patterns by collecting real-time energy consumption data that offer several opportunities to reduce energy consumption by enabling and enhancing energy-efficient practices in production management. (Shrouf and Miragliotta 2015.)

IoT technologies have a key role in smart industry (also called Industry 4.0[6]), where fully-integrated, collaborative manufacturing systems respond in real time to meet changing demands and conditions in the smart factory and even in the supply network, and in customer needs.

According to Rogers (2014) smart manufacturing is related to intelligent efficiency, as they both use ICT to achieve efficiency goals. Intelligent efficiency is energy efficiency made possible by the deployment of affordable next-generation sensor, control, and communication technologies that gather, manage, interpret, communicate, and act upon disparate and often large volumes of data to improve device, process, facility, or organization performance. The energy efficiency improvements can be at multiple layers as showed in Figure 34.

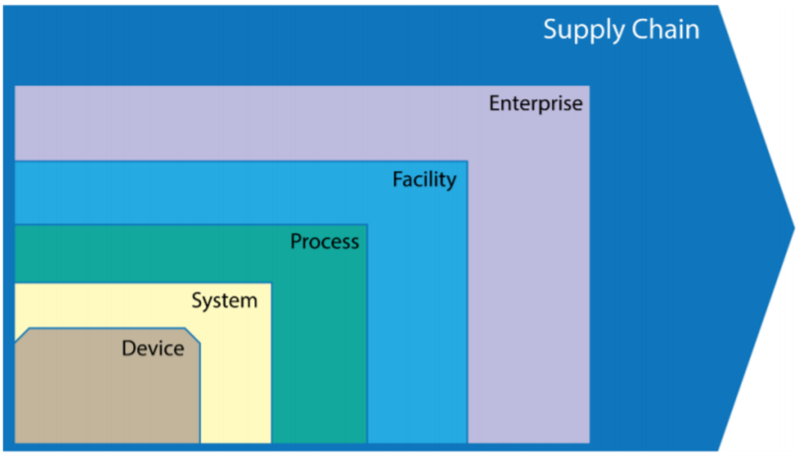


Figure 34: Order of energy savings in manufacturing. Source: Rogers (2014)

The integration of energy data into production management decisions requires not only a network of sensors but also requires e-DSS (energy-Decision Support Systems), the definitions of a set of e-KPIs, visualization tools, optimisation techniques to support energy aware decision-making (Shrouf and Miragliotta 2015).

According to Wang et al. (2018), in order to increase the energy efficiency, a manufacturing company should achieve real-time and seamless dual-way connectivity and interoperability between physical manufacturing systems and enterprise information systems. With the real-time status of machine operation being tracked, the abnormal events of machines such as tool wear, breakdown and efficiency reduction can be also found and managed easily and timely.

Shrouf and Miragliotta (2015) described six main energy related benefits from the adoption of Internet of Things in production management (see Table 12). These optimization areas go beyond the equipment level and include system and process levels (machine scheduling, environmental conditions, resources assignment, operation planning).

Finally, in the evaluation of the net benefits of IoT in industry, the negative effects discussed in the previous chapters of this Task 3 study should be also taken into account. In particular:

[6] Industry 4.0: Digitalisation for productivity and growth. Available at https://www.europarl.europa.eu/RegData/etudes/BRIE/2015/568337/EPRS_BRI(2015)568337_EN.pdf

- The generation of large volume of data destined to be transmitted to Cloud Data Centres (and related impacts
- The manufacturing of increasing number and variety of IoT electronic devices in a wide range of uses to support the IoT infrastructure.

Table 12: Energy efficiency benefits of IoT adoption in production management. Source: Shrouf and Miragliotta 2015

Benefits of IoT adoption (energy efficiency related)	Practices enhanced or enabled by IoT which lead to those benefits
1. Finding and reducing energy waste sources	Comparing energy consumption with production level to find the waste source. Comparing energy consumption for the same process (e.g. heating, molding) in different environments, and then improve.
2. Improving energy-aware production scheduling	Integrating energy consumption data into manufacturing systems to optimize production scheduling Energy efficient jobs routing, when there is sufficient machine flexibility to do so Defining energy consumption for a machine in different configurations (e.g. speed), and then choosing the more efficient machine configuration. Reducing idle time by switching a machine off, if energy consumption in Off/On transition is less than energy waste during idle time.
3. Reducing energy bill 3.1 Avoiding a financial penalty due to breach of the maximum consumption levels 3.2. Reducing energy purchasing cost	Reducing energy consumption at peak time (e.g. load balancing) Negotiating with energy providers and buying energy from several suppliers Making energy purchasing decisions (i.e. determining quantity to purchase) based on real consumption data
4. Efficient maintenance management 4.1 Shifting to condition-based maintenance 4.2 Increasing energy-efficient maintenance 4.3 Increasing accuracy and reliability of equipment by ensuring it is in good condition based on real-time data.	Maintenance based on energy use pattern (e.g. predictive, proactive maintenance).
5. Improving environmental reputation 5.1 Meeting customers' expectations and environmental regulations 5.2 Obtaining environmental certifications (e.g. ISO 50001)	Measuring and reducing the CO_2 footprint coming from production processes, and making such data available to stockholders
6. Supporting decentralization in decision-making at production level to increase energy efficiency.	Using several energy KPIs to evaluate energy usage in production Using visual dashboards on the shop floor to enhance decentralized visual management

4.2.3 Energy systems

IoT can provide a variety of services to energy systems, enabling optimal decisions at both the supply and demand side, and turning them from centralised and one-directional to smart and integrated (Motlagh et al, 2020).

The Figure 35 below demonstrates the plethora of IoT applications in energy systems, which allows for bringing together its subparts into a synergic system.

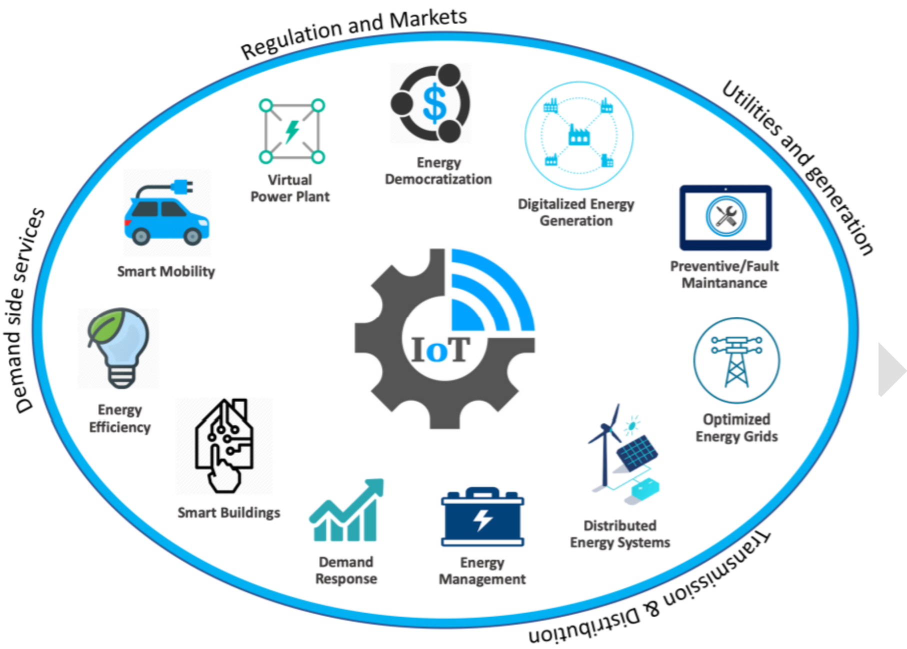


Figure 35: Application of IoT in an integrated smart energy system

Central to a smart energy system integration are smart grids. A smart grid is a concept that integrates information and communication technologies (ICT) with grid power systems, in order to achieve efficient and intelligent energy generation and consumption (Iyer and Agrawal, 2010). IoT can help the energy sector to transform from a centralized to a distributed, smart, and integrated energy system. This can provide major benefits in terms of renewable energy sources (RES) integration, as well as grid stability (Motlagh et al 2020).

Deployment of RES, such as wind and solar, is key towards reaching decarbonisation objectives. However, it is also characterised by challenges related to prediction and control of energy supply (i.e. the intermittency challenge): in an energy system with a high share of Variable Renewable Energy (VRE), matching generation of energy with demand is a big challenge due to variability of supply and demand resulting in mismatch in different time scales (Motlagh et al. 2020).

A lack of management of energy supply and an imbalanced electricity system can lead to energy and material waste due to long distance electricity transportation, electricity network losses, and ultimately, thermal heating and degradation of energy system equipment (Más and Kuiken, 2020). This challenge could be addressed by increasing the physical capacity of the electricity system, but at the same time leading to more resource use (more reserve capacity, cables, transformers, etc.). IoT, on the other hand, can address these challenges and play a vital role in RES integration, by facilitate grid stability by optimising energy demand and supply and address the aforementioned challenges more efficiently (Más and Kuiken, 2020). IRENA (2019) outline the effects of digitalisation and grid smartness across the entire energy system from energy generation from RES to consumption (Figure 36).

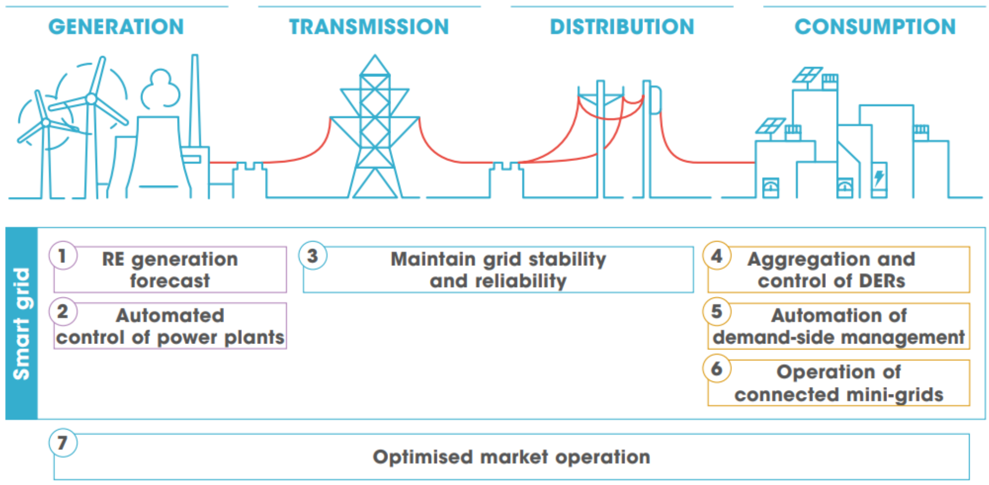


Figure 36: Current state of digitalisation of the energy value chain

In terms of renewable energy generation, the study of weather patterns and collection of real-time data can address the issue of energy generation predictability. General Electric estimates that by implementing digital systems and data analytics, forecast accuracy can increase up to 94% from around 88% today (IRENA 2019). The use of sensors and control systems on power plants such as wind turbines can enable responses to weather and network conditions and optimise generation efficiency.

When it comes to transmission and distribution, IoT can contribute to grid management and network system health, by smoothening out peak load demand that stress and imbalance the system. It can also be used in the context of preventive maintenance, with the use of smart devices and sensors that can indicate and inform about equipment failures.

On the consumption side, digital tools can enable forecasting of energy demand and generation, optimisation of energy reserves, control voltage and frequency, and connect or disconnect from the main grid, facilitating local energy generation when sites are in remote areas and not connected to the main grid. (IRENA 2019). IoT offer solutions for the automation of demand-side management and contribute to the establishment of a smart grid.

Mas and Kuiken (2020) also recognise the role of IoT in improving the matching of demand with the available supply. Demand Side Response (DSR) could consider not only the timing of production and consumption, but also the location of consumption and production, potentially bringing even more efficient results. Considering the growing amount of distributed RES (e.g. solar panels or – onshore – wind turbines), local demand and supply matching could reduce network losses: in general, the less electricity must be transported, the less electricity will be wasted. Also, DSR could reduce the need for spinning reserves[7], which could reduce the amount of energy wasted for balancing the electricity system.

In order to apply DSR, sufficient data on consumption and production patterns need to be available on the (expected) production and consumption, and the local network status (Más and Kuiken, 2020). Moreover, a response mechanism should be present. Such a mechanism could simply be a consumer, switching on or off equipment at exactly the right moment, but will more likely be an automated mechanism, a configuration in which e.g. an appliance (or a management interface connected to the appliance) is able to switch itself (or it) on or off, or to reduce or increase the consumed loads by the appliance.

Heat pumps are considered to be a major technology to provide flexibility to the power system meanwhile providing efficient heating and cooling solutions to residential buildings. The technology is supported by increasing efficiency, the deployment of computing and communication technology and increased renewable electricity generation. Potential benefits of peak reduction on an aggregate level involve lower electricity generation costs (which is called merit order effect), less need for peak generation reserve power plants and less need for transmission capacity (Fischer and Hadani, 2017).

[7] The spinning reserve is the extra generating capacity that is available by increasing the power output of generators that are already connected to the power system

Such optimisation is also achieved with the use of smart appliances and devices; such technologies are further studied in the following section.

Table 13 summarises the benefits of different applications of IoT in the energy sector. Motlagh et al. 2020 identifies possible benefits both in the field of the energy supply regulation and markets and in the field of energy supply (see table below).

Table 13: Benefits of the applications of IoT in the energy sector (1): regulation, market, and energy supply side. Source: Motlagh et al., 2020.

	Application	Sector	Description	Benefits
Regulation and market	Energy democratization	Regulation	Providing access to the grid for many small end users for peer to peer electricity trade and choosing the supplier freely.	Alleviating the hierarchy in the energy supply chain, market power, and centralized supply; liquifying the energy market and reducing the prices for consumers; and creating awareness on energy use and efficiency
	Aggregation of small prosumers (virtual power plants)	Energy market	Aggregating load and generation of a group of end users to offer to electricity, balancing, or reserve markets.	Mobilizing small loads to participate in competitive markets; helping the grid by reducing load in peak times; Hedging the risk of high electricity bills at peak hours; and improving flexibility of the grid and reducing the need for balancing assets; Offering profitability to consumers.
Energy Supply	Preventive maintenance	Upstream oil and gas industry/ utility companies	Fault, leakage, and fatigue monitoring by analyzing of big data collected through static and mobile sensors or cameras.	Reducing the risk of failure, production loss and maintenance downtime; reducing the cost of O&M; and preventing accidents and increasing safety.
	Fault maintenance	Upstream oil and gas industry/ utility companies	Identifying failures and problems in energy networks and possibly fixing them virtually.	Improving reliability of a service; improving speed in fixing leakage in district heating or failures in electricity grids; and reducing maintenance time and risk of health/safety.
	Energy storage and analytics	Industrial suppliers or utility companies	Analyzing market data and possibilities for activating flexibility options such as energy storage in the system.	Reducing the risk of supply and demand imbalance; increasing profitability in energy trade by optimal use of flexible and storage options; and ensuring an optimal strategy for storage assets.
	Digitalized power generation	Utility companies & system operator	Analysing big data of and	Improving security of supply; improving asset usage and management; reducing

			controlling many generation units at different time scales	the cost of provision of backup capacity; accelerating the response to the loss of load; and reducing the risk of blackout.

4.2.4 Homes and Offices Buildings

The importance of improving the energy efficiency at homes and offices derives not only from the fact that buildings are responsible for approximately 40% of energy consumption and 36% of CO2 emissions in the EU[8], but also from future trends: the IEA Central Scenario (IEA 2019a) suggests that electricity use in buildings is set to nearly double from 11 petawatt hours (PWh) in 2014 to around 20 PWh in 2040 globally.

As indicated in the previous section, IoT at building level can offer a variety of benefits in terms of energy efficiency, not only for the building itself but the energy system as a whole.

The concept of Smart Building could be defined as a set of communication technologies enabling different objects, sensors and functions within a building to communicate and interact with each other and also to be managed, controlled and automated in a remote way (European Commission, 2017).

Building Automation and Control Systems (BACS) with the use of sensors, communication protocols and automated processes allow for the control of the building's operations, including adjusting HVAC (Heating, Ventilation, Air Conditioning) systems according to ambient conditions, or adjusting lighting levels based on room occupancy. Thus, they provide various services ranging from comfort to safety, but also energy efficiency within the building.

At the same time, and as described in the previous section, such automation and connectivity allows an interaction with the wider grid and all the way with the energy production source.

The following graphs Figure 37) demonstrates the increased development in smart homes in millions and also the penetration rate in Europe.

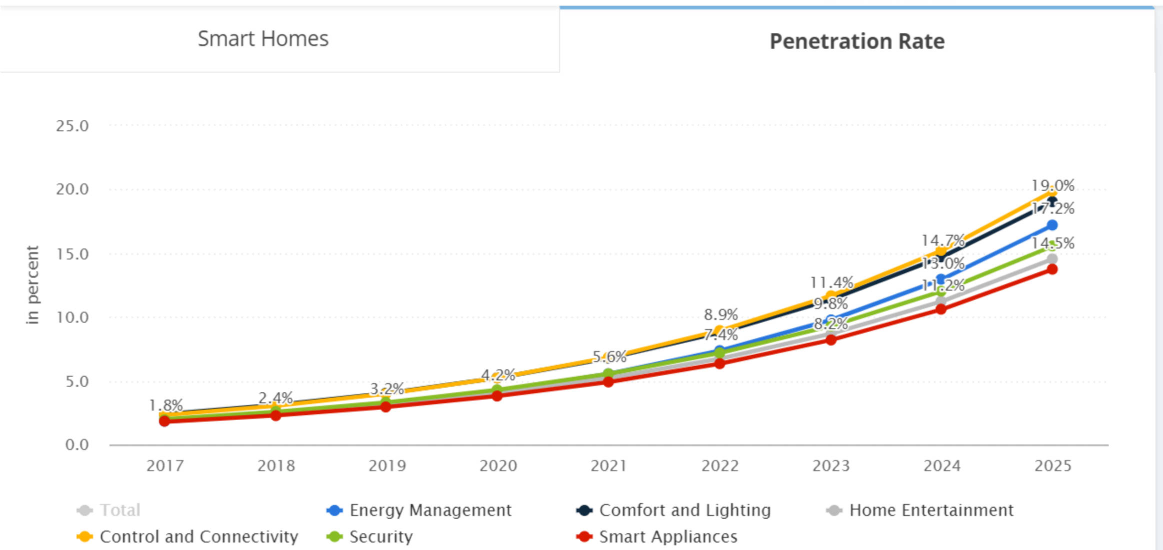


Figure 37: Penetration Rate of smart home devices. *Source: Statista, November 2020,* [*https://www.statista.com/outlook/279/102/smart-home/europe*](https://www.statista.com/outlook/279/102/smart-home/europe)

Despite the expected increase in the coming years, the penetration rate of smart homes is still at a stage of early, tech-oriented adopters (Serrenho and Bertoldi, 2019).

[8] https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en

Table 14 offers a list of various BAC system products and also components that are providing data input to the system (VHK and Viegand Maagøe, 2020):

Table 14: BACS products and related components / sensors providing data inputs

BAC system product	Components providing data input
heating, ventilation (including window openings) and air conditioning (HVAC)	Temperature sensors
domestic hot water (DHW)	CO2 sensors
solar shades	Humidity sensors
lighting	Presence detectors
electrical power distribution	Solar radiation sensors
access control & security	Outdoor wind speed meter
fire safety	Light meter
	Domestic cold and hot water meters
	Electricity meters
	Heat and other energy meters
	Door and window opening sensors
	Smoke and fire detectors
	Access control detectors
	User setting for desired indoor quality level, scheduling

A main feature of smart buildings is the use of smart appliances, meaning appliances that are communication enabled (VITO, 2016). This is achieved with the use of IoT technologies, which can contribute to energy efficiency by containing energy saving features (e.g. alerting when the refrigerator door is left open or allowing for demand response flexibility. Such IoT technologies and systems are described below.

Sensors, as can also be derived from the table above, are a key technology for the implementation of BACS and smart buildings. Temperature sensors, for instance, generate data of ambient conditions, while Passive Infrared (PIR) sensors can detect the presence of humans inside spaces. Such data can determine the best time for turning on or off the ventilation and cooling systems or the lighting system, thus saving energy Motlagh et al 2020.

Data generation alone is only part of a connected system. Another technology crucial for the composition of a smart building are **wireless communication systems**. Those systems communicate data from the sensors to other IoT devices, sensors and mobile app controllers or displays that offer an interface with consumers. Depending on the application various protocols are used. Beyond the power demanding Wi-Fi, other communication technologies are deployed, such as ZigBee, Bluetooth low energy (BLE), or LoRa, which offer low power, interoperable and energy efficient solutions (VHK and Viegand Maagøe, 2020; Motlagh et al 2020).

At the other end of the system are **consumers** who still play a central role in the delivery of energy efficiency by those systems. Serrenho and Bertoldi (2019) point to the correlated of potential of energy savings in smart homes with the feedback being provided to final energy consumers. An example of such interaction takes place via In-Home Displays, which are platforms allowing access to information related to the consumption of connected devices, energy prices and utility load fluctuations, as well as the ability to remotely control appliances for a customised service and optimised efficiency. This review of 46 studies where consumers interacted registered energy savings reaching up to more than 15%. This is consistent with Darby (2016), reporting a norm of savings from direct feedback (from meters to an associated display monitor) that range from 5-15%.

Horner et al 2016 point out that energy waste in buildings can be addressable by ICT interventions, such as the use of smart meter technology coupled with displays can provide real-time load information, which should cause a rational (in the classical economic sense) customer to reduce consumption. Building energy management systems (BEMS), including technology like programmable thermostats and occupancy sensors, can reduce the need for human hands (and minds) to make routine energy-saving interventions. BEMS match heating, ventilating, and air conditioning (HVAC) operation to required load and analyze consumption patterns to detect faults. Empirical studies of BEMS have found energy savings of 7%–23%.Such benefits, on the other hand, depend on various factors, and therefore cannot be taken for granted, as the concept of smart buildings does not itself necessarily translate into energy savings. Firstly, it is important to distinguish devices which are smart, in the sense that they can be connected and controlled remotely, from those that are intelligent, meaning those with an ability to make decisions based on daily habits of human beings (CarbonTRACK, 2020).

Furthermore, studies point out that the use of home management systems and their ability to stimulate on energy-saving user behaviour, depends on a households' willingness and an ability to engage to the information and features provided (Buchanan et al 2015; Nilsson et al 2018; Vassileva et al, 2013). Furthermore, several studies reporting energy savings are based on consumer surveys, which could suffer from the Hawthorne effect, according participants alter their behavior simply because they are aware that the study is taking place (Horner et al 2016; Schwartz et al 2013).

Another factor refers to the type of information provided and the way the information is presented to users. Darby 2016 indicates the difference between direct and indirect feedback, i.e. feedback that has been processed in some way before reaching the energy user, normally via billing. High energy users may respond more than low users to direct feedback. Indirect feedback, on the other hand, is usually more suitable for consumption of changes in space heating, household composition and the impact of investments in efficiency measures or high-consuming appliances.

Another factor with a role in the delivery of actual efficiencies is the way systems are installed. Studies from the US note that even if programmable thermostats for heating and cooling control could theoretical deliver 5–15% energy reductions compared to manual thermostats (Peffer et al 2013), factors such as poor installation, design and usability (such as difficult to understand interfaces, small buttons, inaccessible installation location) could discourage consumer engagement and cancel those savings out (Meier et al. 2011, Pang et al 2021).

Lastly, beyond the direct consumption of such systems (first-order effects) and the uncertainty of second-order effects presented above, third-order effects (not further examined in this study) could also emerge, such as the rebound effects. An example is the likelihood of advanced lighting control technologies leading to the installation of more lights in the system Aebischer and Huser (2000).

IEA (2019a) suggests that, assuming limited rebound effects in consumer energy demand, digitalisation in residential and commercial buildings, including smart thermostats and smart lighting, could cut their total energy use between 2017 and 2040 by as much as 10% compared with the IEC Central Scenario Figure 38. Cumulative energy savings over the period to 2040 would amount to 65 PWh – equal to the total final energy consumed in non-OECD countries in 2015.

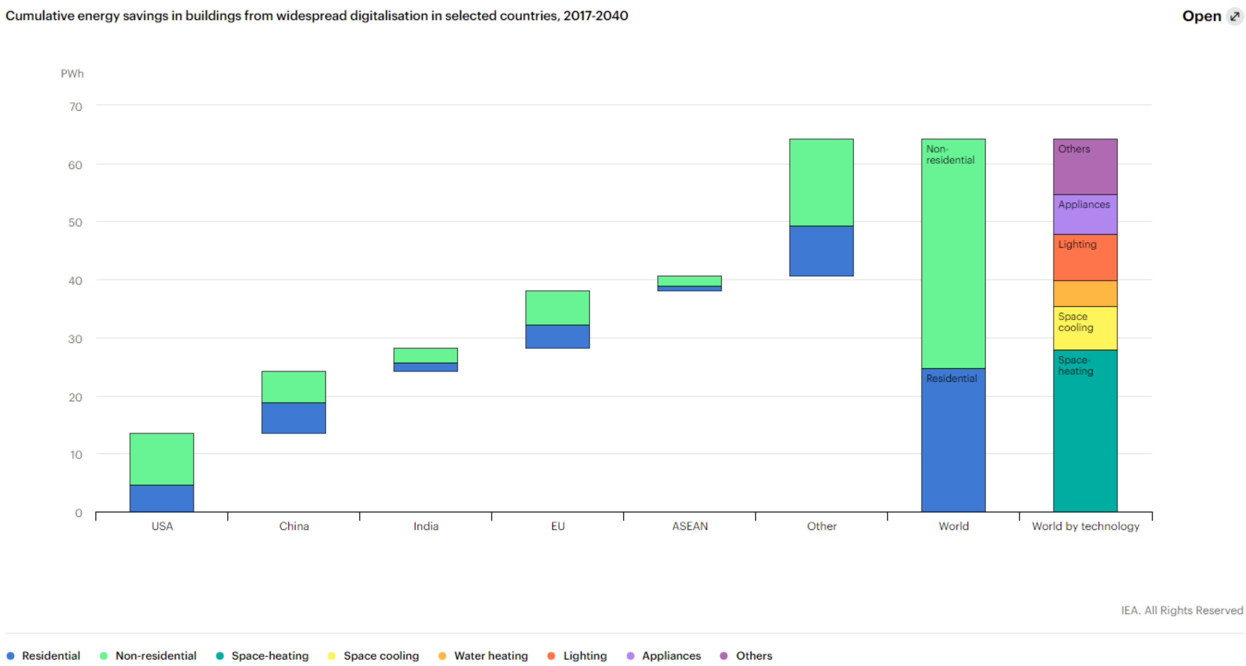


Figure 38: Cumulative energy savings in buildings from widespread digitalisation (in PWh). EU; residential: 3.95 PWh; non-residential: 5.94 PWh World; residential: 24.76 PWh; non-residential: 39.50 PWh World; space heating: 27.94; space cooling: 7.53 PWh; water heating: 4.44PWh; lighting: 7.93PWh ; appliances: 6.87PWh; other: 9.55PWh

Assuming an optimal level of installation and operation of BAT/BEMS or BAT/HEMS in 100% of EU buildings, Waide (2014) estimates incremental annual energy savings which would peak at approximately 50 Mtoe in 2035 for service sector buildings and at approximately 100 Mtoe in the year 3029 in residential buildings (Figure 40).

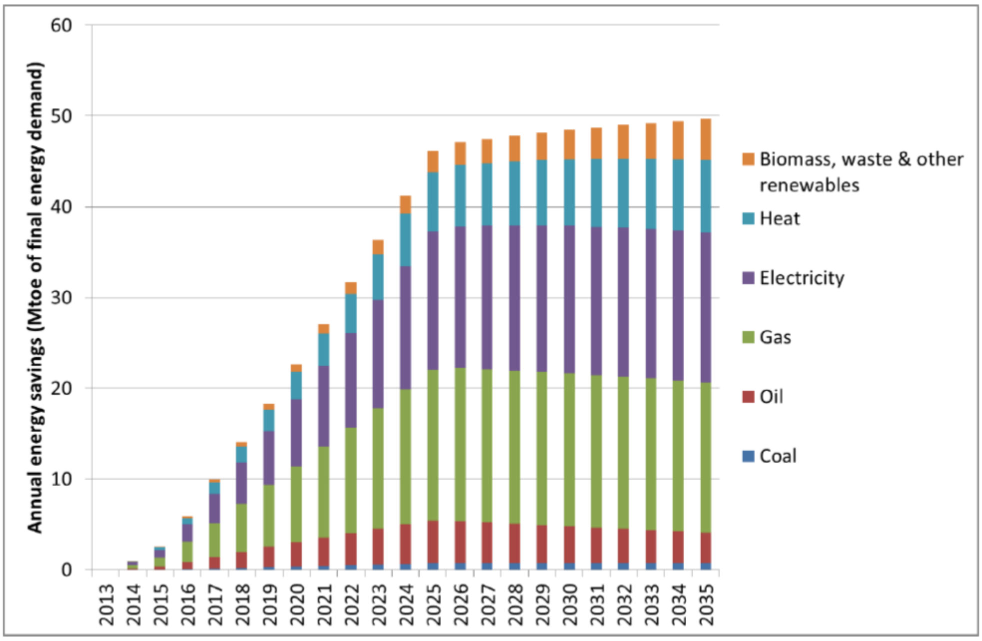


Figure 39: Service sector building additional energy savings under the Optimal Scenario compared with the Reference Scenario from 2013 to 2035.

4.2.5 Transport

IoT deployment could have a significant impact on transport systems as well. The use of sensors, advances in satellite communications and processing of data can optimise route planning and reduce fuel use in the sectors of commercial aviation and shipping (IEA, 2017).

However, the biggest changes could be witnessed in the digitalisation of road transport. Sensing, connectivity and automation technologies could fundamentally transform the movement of people and goods, with the uptake of automated, connected, electric and shared (ACES) mobility (IEC, 2017). Similarly to the case of buildings, IoT in transport can improve the driving experience and safety via automated driving technologies, while real-time traffic information, smart parking systems and eco-driving functions can lead to selecting optimal routes, and providing fuel savings (Motlagh et al 2020). An IEA study found that applying digital solutions to truck operations and logistics could reduce road freight's energy use by 20-25% (IEA, 2017).

The graph below Figure 40 (IEA 2019a) demonstrates the projected impact of digitalisation on energy use in road traffic for the period between 2015 and 2050.

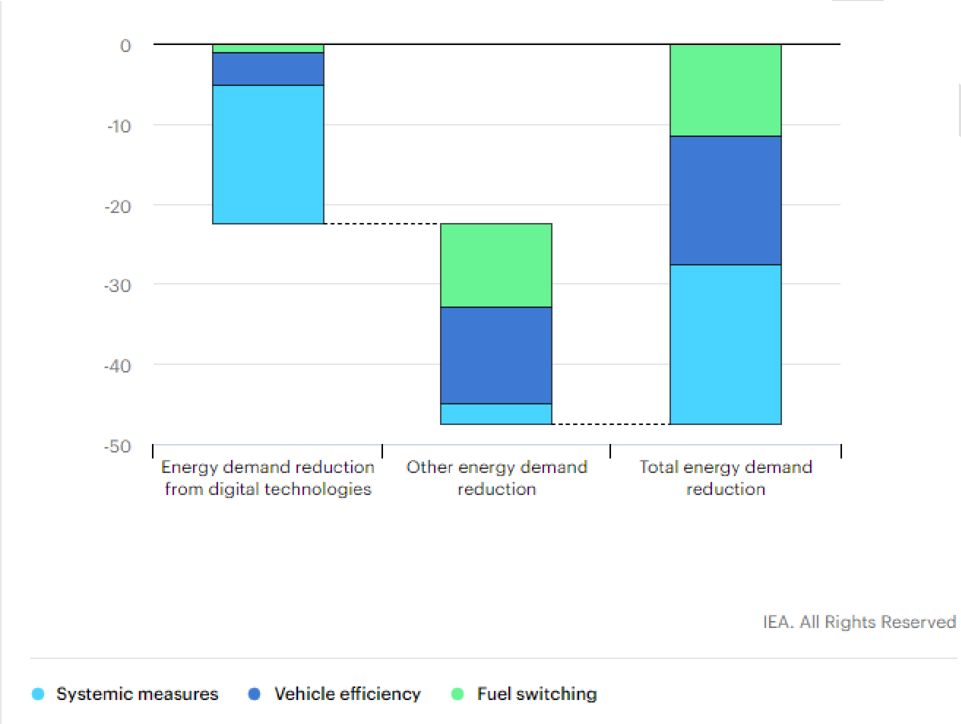


Figure 40: Impact of digitalisation on energy use in road freight 2015-2050.

These benefits are always presented keeping in mind potential associated rebound effects (IEA, 2017).

4.3 IoT trends and challenges

The application and position effects deriving from ICT use and digitalisation are also associated with challenges. A list of challenges and solutions are provided by Motlagh et al 2020 (see Table 15).

Table 15: Challenges and current solutions of using IoT in the energy sector.

Challenge	Issue	Example Solution	Benefit
Architecture design	Providing a reliable end-to-end connection	Using heterogeneous reference architectures	Interconnecting things and people
	Diverse technologies	Applying open standard	Scalability
Integration of IoT with subsystems	IoT data management	Designing co-simulation models	Real-time data among devices and subsystems
	Merging IoT with existing systems	Modelling integrated energy systems	Reduction in cost of maintenance
Standardization	Massive deployment of IoT devices	Defining a system of systems	Consistency among various IoT devices
	Inconsistency among IoT devices	Open information models and protocols	Covering various technologies
Energy consumption	Transmission of high data rate	Designing efficient communication protocols	Saving energy
	Efficient energy consumption	distributed computing techniques	Saving energy
IoT Security	Threats and cyber-attacks	Encryption schemes, distributed control systems	Improved security
User privacy	Maintaining users' personal information	Asking for users' permission	Enables better decision-making

A major challenge for the deployment of IoT solutions in energy systems is the energy consumption of IoT themselves. Section 3 of this report, presented challenges related to the generation and submission of large amounts of data and the impact on the ICT system that this entails. At the same time, efforts at achieving better efficiency are made, including setting sensors to sleep mode when not used and establishing efficiency communication protocols (Motlagh et al 2020).

Besides the challenges associated with the direct consumption of ICT, there are also uncertainties about the delivery of second-order effects, and the emergence of third order effects. Positive substitution effects, for instance, can often be "incomplete", or their efficiency may be cancelled out by rebound effects. For example, the ICT-enabled benefits of e-commerce and optimised logistics might be overcompensated by increased volume of deliveries, or consumers using e-commerce only partly for their shopping without saving trips (Berkhout and Hertin (2001).

Noteworthy are of course other challenges too, which may not be energy-related, but are nevertheless considered. One challenge is related to user privacy of the data gathered by IoT and also security. For example, data generated by electric vehicles or smart appliances at home might reveal information about where the user is at a given time or what their sleeping patters are. On one hand, such data may be exploited commercially, and on the other and they might be susceptible to cyberattacks and security breaches (IRENA, 2019)

Finally, there is a challenge of standardisation for the protocols and procedures used to establish communications are large scale, related to data sharing to contracts and payments.

Amongst the solutions to aforementioned privacy and energy management challenges is blockchain technology. Blockchain allows for information exchange between people and devices without the involvement of a third party, whether this is related to energy distribution or payments (Motlagh et al 2020; IRENA, 2019). Provided that challenges such as reducing cost and ensuring privacy are considered, blockchain technology can bring multiple benefits from an energy management perspective. Consumers and prosumers can receive information about price signals and energy costs, and perform trades of their energy surplus or flexible demand in a decentralised and transparent way. Such platforms provide incentives for demand response and smart management of their energy needs, enabling the formation of local microgrids which in turn facilitates RES integration, reduces transmission losses and increases network stability. It has to be noted however, that the use of blockchain technology itself is associated with energy consumption, which can be high compared to the transactions performed. The energy demand for blockchain technology applications are very much dependent on the blockchain architecture used (Andoni et al, 2018; Sedlmeir et al, 2020).

Energy harvesting

The development of IoT is associated with the use of low-power sensors. Sensors are undertaking simple tasks such as measurement and communication that require small quantities of energy, but are present in large numbers and geographically dispersed. When grid connection is lacking, such applications have to rely on costly and often short-lived batteries that also have a considerable impact on the environment (Ellis et al, 2015 ; Zeadally et al 2020; Elahi et al 2020). Therefore, ensuring high efficiency of IoT applications is important. One solution to this problem is energy harvesting, i.e. the process of conversion of ambient energy into electrical energy (Figure 41) (Elahi et al 2020). Energy can be harvested by sources such as wind solar energy, wind energy, mechanical energy or radio frequency energy (Table 16).

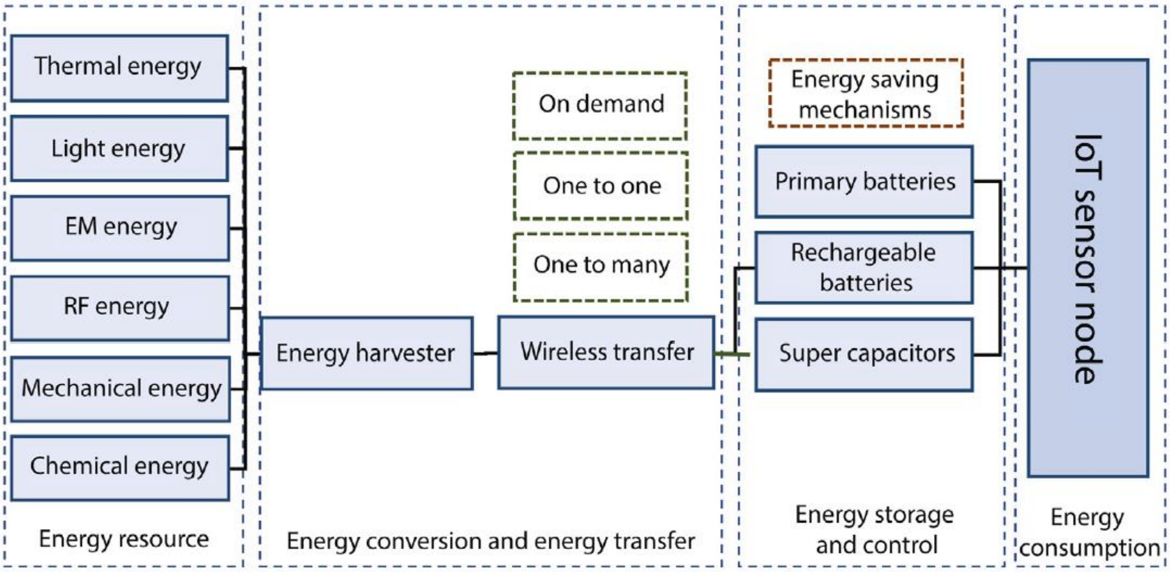


Figure 41: A block diagram of an energy harvesting system. Source: Zeadally et al 2020.

Table 16: Comparison of energy harvesting sources. Elahi, 2020

Source	Method	Merit	Power Density	Weakness	Applications
Aeroelastic energy	FSI and Piezoelectric	High efficiency Controllable	0.6 lW/cm^2 [48]	Material can break	Aerospace vehicle
Mechanical energy	Electromagnetic, and Piezoelectric	High efficiency Controllable	0.819 lW/cm^2 [32]	Material can break	PEH, road buffers, TENG
Light Energy	Photovoltaic	Predictable, Mature	[181] 5–100 mW/cm^2 (solar) [182] 0.5–1000 lW/cm^2 (Indoor)	Expensive, light not steadily available	Biometric, Agriculture, monitoring, ZNE building, indoor and portable devices
Wind energy	Piezo turbine	Low wind speed can work	[90] 4–50 lW/cm^2	Wind not steadily available	Agriculture
Sound energy	coherence resonance	Clean, sustainable	[85] 6.02 lW/cm^2	Big energy loss, highly variable	Structure monitoring, environment monitoring
Radio frequency energy	Rectenna	Continuous available, carry and process information simultaneously	[186] 0.01–0.3 lW/cm^2	Efficiency decrease with distance	Sensor, Nuclear, wirelessly powering
Pyroelectric energy	Pyroelectricity	waste heat Can be used	[187] 48.57 lW/cm^2	Low efficiency	waste energy Plants

IoT sensors can optimise their efficiency in various ways. One way is radio optimisation, whereby the power is tuned to low to consume less energy when the nodes are close and tuned to full when the nodes are far away. Another example of energy efficiency is the use of scheduling techniques, whereby the data is transmitted only when necessary, and when no data are to be sent, the nodes are put to sleep. Finally, different wireless standards are more efficiency than others and each appropriate for different applications. Therefore, making the right choice of standard wireless standard can deliver higher energy efficiency Table 17) (Zeadally et al 2020).

Table 17: Energy consumption of various components used in IoT. Source: Zeadally et al 2020

	Component	Power/Current consumption
Wireless technology	Wi-Fi	835 mW
	Zigbee node	36.9 mW
	MiMAX node	36.78–36.94 W
	Bluetooth	215 mW
	BLE	10 mW
	Cellular	0.1–0.5 W
	LoRa	100 mW
Typical sensing devices	Temperature/humidity	0.2–1 mA
	IR	16.5 mA
	Ultrasonic	4–20 mA
	PIR	65 mA
	Light	0.65 μA
	Camera	270–585 mA
IoT node/gateway	WASP mote	9 mA
	Pi	100–500 mA
	Xbow	17.5–19.7 mA
	Arduino	3.87–13.92 mA

Another interesting concept related to energy harvesting is the Zero Energy Appliance (ZEAP) (Ellis et al, 2015; Meier and Siderius, 2017). As technologies for energy harvesting are improving and efficiencies of products ZEAPs can be an attractive concept for IoT applications. Many ZEAPs, especially sensors, will replace battery powered devices or will be new devices and therefore will not have an impact on electricity consumption from the grid. For larger devices the qualitative impact is that developments towards ZEAPs could also stimulate the development of more efficient components and devices. (Ellis et al, 2015; Meier and Siderius, 2017)

5 Conclusion

Task 3 provided an analysis of the impact of ICT devices on energy consumption from a systemic level. First, an assessment of the energy consumption associated with the manufacturing of ICT is presented, confirming this lifecycle stage as highly relevant to the overall carbon footprint of ICT systems. That is the case especially for the manufacturing of integrated circuits, essential elements in components related to data processing, storage and connectivity. In the second section, the focus was shifted towards the energy consumption during the use phase of ICT systems, where the question of whether technological improvements leading to higher efficiencies are sufficient to compensate for the significant and ever-increasing data demand that is forecasted. Results from the literature are characterised by methodological differences and challenges of data availability, but forecasts range from consumption levels remaining stable in optimistic approaches, to significant increase in some others, should there not be further efficiency gains and overturning of current trends. Finally, the positive effect of systemic optimisation expected by ICT systems are qualitatively assessed in the third section. Those are realised by the efficiencies brought about by the expansion of IoT technologies and their application in a wide range of sectors.

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List of abbreviations and definitions

ΑΒΓ Alpha Beta Gamma

ΔΕΖ Delta Epsilon Zeta Delta Epsilon Zeta Delta Epsilon Zeta Delta Epsilon Zeta Delta Epsilon Zeta Delta Epsilon Zeta

ΗΘΙ Eta Theta Iota

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Annexes

Annex 1. Literature data of energy intensity in manufacturing of key ICT components

Table 18 presents some literature data of energy intensity in manufacturing of key ICT components. The energy intensity is often expressed as quantity of energy per square centimetre of component (e.g. integrated circuits) which is considered a much more accurate scaling parameter than the than the weight (Fraunhofer IZM et al., 2020).

Table 18: Literature data on manufacturing data of key ICT components

Component	Primary Energy	Electricity needed in manufacturing	Source
Integrated Circuits	Not Avaialable	3 kWh/cm^2 for processors and application specific integrateted circuits and 2 kwh / cm2 for memories	(Ercan et al., 2016)
Generic ICs	26730 Mj	21.415MJ/cm^2 = 5.83 kWh/cm^2	(Fraunhofer IZM et al., 2020)
LCD Screen (including the touch layer)	Not available	0.1 kWh/cm^2	(Ercan et al. 2016)
LCD Display Smartphone	256 Mj	245 Mj /100 cm^2 = 0.68 kWh/cm^2	(AU Optronics Corp. 2020) (Fraunhofer IZM et al., 2020)
AMOLED Display Smartphone	364 MJ	245 Mj /100 cm^2 = 0.68 kWh / cm2	
LCD Display Tablet	213 MJ	204.29 Mj /100 cm^2 = 0.57 kWh/cm^2	