The ICT sector, climate and the environment

Interim report of the working group preparing a climate and environmental strategy for the ICT sector in Finland

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Ministry of Transport and Communications, 2020

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Abstract

The Ministry of Transport and Communications appointed a working group to develop a climate and environmental strategy for the ICT sector for the period from 1 November 2019 to 30 November 2020. The aim is to form a common view on the climate and environmental impacts of the ICT sector and recommend measures to control them. This interim report of the working group compiles information about the ICT sector's environmental impacts and creates a situational picture on which further discussions on needed measures can be based.

The report examines the ICT sector's twofold role in climate and environmental issues. The ICT sector needs infrastructure that consumes energy and materials and causes emissions. The volume of data continues to grow considerably due to new technologies and applications, which presents a challenge for developing energy-efficient solutions. In addition, ICT terminals involve large material streams and the amount of electronic waste increases rapidly. The ICT sector can play a significant role in making society more climate-friendly and environmentally-friendly. In addition to enabling reductions in emissions, ICT supports adaptation to climate change and environmental and climate research. It is difficult to assess and compare the climate and environmental impacts of the ICT sector due to the lack of uniform and systematic ways to report on energy consumption and emissions in the sector, or emissions reductions in other sectors.

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Raportissa tarkastellaan ICT-alan kahtalaista roolia ilmaston ja ympäristön kannalta. ICT-ala tarvitsee infrastruktuuria, joka aiheuttaa energian- ja materiaalinkulutusta ja päästöjä. Datamäärät kasvavat voimakkaasti uusien teknologioiden ja sovellusten myötä, ja asettavat haasteen energiatehokkaiden ratkaisujen kehittämiselle. Lisäksi ICT-päätelaitteisiin liittyy suuria materiaalivirtoja ja elektroniikkajätteen määrä kasvaa nopeasti. ICT-alalla on merkittävä rooli ilmasto- ja ympäristöystävällisemmän yhteiskunnan mahdollistajana. Päästövähennysten mahdollistamisen lisäksi ICT tukee ilmastonmuutokseen sopeutumista ja ilmaston ja ympäristön tutkimusta. ICT-alan ilmasto- ja ympäristövaikutusten vertailua ja seuraamista vaikeuttaa, että käytössä ei ole yhtenäisiä ja systemaattisia tapoja raportoida alan energiankulutuksesta ja päästöistä tai päästövähennysvaikutuksista muilla aloilla.

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I rapporten granskas IKT-branschens dubbla roll med tanke på klimatet och miljön. IKT-branschen behöver infrastruktur, vilket orsakar energi- och materialförbrukning och utsläpp. Mängden data ökar kraftigt i och med ny teknik och nya IKT-tillämpningar, och utgör en utmaning för utvecklingen av energieffektiva lösningar. Dessutom medför IKT-utrustningen stora materialflöden och mängden elektronikavfall ökar snabbt. IKT-branschen har en viktig roll i att möjliggöra ett mer klimat- och miljövänligt samhälle. Förutom att den tillåter utsläppsminskningar stöder IKT anpassningen till klimatförändringen och forskning kring klimat och miljö. Jämförelsen och uppföljningen av IKT-branschens klimat- och miljökonsekvenser försvåras av att det inte finns enhetliga och systematiska sätt att rapportera om energiförbrukningen och utsläppen inom branschen eller om effekterna av utsläppsminskning inom andra branscher.

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PREFACE

The Ministry of Transport and Communications of Finland has long been working to reduce the climate and environmental impacts of transport. However, it is only recently that the climate and environmental impacts of ICT have come under discussion. Finland is leading the way in the formulation of a national climate and environmental strategy.

The current document is the interim report of the working group appointed by then Minister of Transport and Communications Sanna Marin to prepare a climate and environmental strategy for the ICT sector. The working group aims to publish its final report in autumn 2020. This interim report paints a situational picture of the positive and negative climate impacts of the ICT sector, i.e. the sector's carbon handprint and footprint as well as its other environmental impacts.

This quite comprehensive report would not have been possible without constructive collaboration and considerable effort on the part of the working group member organisations and other experts. The work carried out to date provides an excellent foundation for the working group to deliberate on recommendations for action.

Climate change and environmental degradation are among the most serious challenges of our times. It is important to understand how the negative impacts of the ICT sector on climate and the environment can be minimised. A positive finding is that the rise in the sector's electricity consumption has been kept at a reasonable level despite growing data volumes and that the sector's carbon dioxide emissions in Finland are small, thanks to our clean electricity production.

The potential of the ICT sector in all areas of society gives much cause to hope that a significant reduction in emissions can be accomplished. Finnish expertise also has much to contribute towards this aim.

Increasing the sector’s energy efficiency and maximising its positive impacts call for ongoing development. New technologies create opportunities and challenges alike, and it is important for us to gain a better understanding of these in order to move ahead in the right direction. Likewise, solutions must be identified for better managing the material flows of end user devices. These topics will be discussed further in the next phase of the strategy work.

Päivi Antikainen
May 2020

1 Introduction

1.1 Background and aims

The Ministry of Transport and Communications appointed a working group on 1 November 2019 to prepare a climate and environmental strategy for the information and communications technology (ICT) sector. Achieving the objective of a carbon-neutral Finland by 2035 will require emissions to be reduced in all sectors. While the ICT sector delivers solutions that promote emission reductions, attention must also be paid to the sector's own carbon footprint and its other impacts on the environment.

Climate and environmental issues in the ICT sector have only recently begun to garner wider attention. Assessments of the positive impacts of ICT on climate change mitigation have been published both in Finland and internationally. Media headlines have also raised concerns over the growing carbon footprint and materials consumption of the sector owing to the constant rise in the volume of data transmitted and the market launch of new devices.

Telecommunications companies, among others, have for long conducted studies on their own climate and environmental impacts. Finnish universities and research institutes have likewise studied the climate and environmental impacts of the ICT sector from a variety of perspectives. The Ministry of Transport and Communications also prepared an action programme for a green ICT sector as part of its official duties in 2013. The implementation of the programme included the preparation of a sustainability rating system for data centres, to be used as a tool in data centre design[1], and a study on the energy consumption of media content[2]. In the early 2010s, the International Telecommunication Union (ITU) issued recommendations on methodologies for assessing the environmental impacts of the ICT sector.[3]

The conclusion reached in the 2013 action programme of the Ministry of Transport and Communications remains relevant: sustainability issues in the ICT sector must be addressed with comprehensive, public and universally accessible data. Consistent

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[1] Ministry of Transport and Communications 2014: TIKO - Sustainability rating system for data centers. User manual, v0.4 for New Constructions.
[2] VTT Technical Research Centre of Finland 2015: Preliminary report: TV-sisältöjen monikanavaisen jakelun energiankulutuksen arviointi [Assessment of energy consumption of multichannel TV content distribution].
[3] ITU-T 2011: Overview and general principles of methodologies for assessing the environmental impact of information and communication technologies.

and transparent methods are required to measure and monitor the negative and positive environmental and climate impacts of the components of the ICT production chain and of digital services, as well as to guide activities. The fast pace of development in the ICT sector adds to the challenges of impact assessment.

This interim report provides a description of the climate and environmental impacts of the ICT sector in Finland compiled by a broad-based working group consisting of representatives of government, civil society organisations, higher education institutions and businesses. The description is based on the best information currently available. Going forward, it is clear that the ICT sector impacts picture will be further refined. Finland stands at the vanguard when it comes to broad-based cooperation in examining the climate and environmental impacts of the ICT sector, as is only natural for a leading country in digitalisation.

This report looks at the sector's energy consumption and other environmental impacts as well as the utility of ICT in furthering emission reductions and other environmental benefits. The report also provides a compilation of potential tools to reduce the negative environmental impacts of the sector. This range of tools can aid in further deliberation and provide a foundation for debate on the topic. The final report including concrete proposals for action will be published in November 2020. Some of the themes addressed here only briefly will also be elaborated upon in the final report.

The UN 2030 Agenda for Sustainable Development was globally adopted in 2015. Its seventeen Sustainable Development Goals (SDGs) and respective targets seek to resolve the key social, economic and environmental global challenges by 2030. Debate and research on the links between digitalisation and ICT and the achievement of the SDGs has also started.[4]

The recognised strengths of Finland in sustainable development research include our high level of education and the ensuing competences as well as the general stability of Finnish society and its systems. Our key challenges are climate change and excessive consumption of natural resources as well as economic and employment development.[5] Ways to address these challenges can be found through even better utilisation of the potential of ICT for emission reductions and higher resource efficiency while at the same time finding markets for Finland's expertise in fields including the design of software, energy-efficient devices and IT areas.

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[4] IIASA 2019: TWI2050 - The World in 2050. The Digital Revolution and Sustainable Development: Opportunities and Challenges.
[5] Prime Minister's Office 2019: Towards the Finland We Want 2050. State of Sustainable Development in 2019 in Light of Indicators and Comparative Studies.

1.1.1 Organisation of strategy work

A representative to the strategy working group was appointed by 28 of the organisations invited by Ministry of Transport and Communications to take part. Two sub-groups were set up to organise the practical efforts of the working group. Besides the member organisations of the working group, the meetings of the working group and the sub-groups also heard presentations by experts on the various climate and environmental aspects of the ICT sector.

The two sub-groups focused on the following topics: 1) infrastructure: data centres, communication networks and end user devices examined from the perspectives of energy and materials consumption and ways to curb these, and 2) applications: software and tools provided by the sector to other industries for reducing greenhouse gas emissions and negative environmental impacts, including the challenges and opportunities of new technologies. The work has been reported via an open website[6] and at public events.

In addition to the expertise supplied by the working group's member and partner organisations, several additional studies have been carried out and commissioned to support the work of the strategy group. The Finnish Transport and Communications Agency Traficom has gathered indicators on the climate and environmental issues of communication networks from telecommunications companies. The Ministry of Transport and Communications has commissioned studies on end user device material flows (Finnish Environment Institute SYKE) and the benefits of ICT in reducing greenhouse gas emissions in the energy sector (VTT Technical Research Centre of Finland). While the final reports on these studies will be issued separately at a later date, this report already draws on their interim findings. Traficom commissioned an assessment (Deloitte) of the climate and environmental impacts of emerging technologies. The Ministry of Transport and Communications has been drafting a logistics digitalisation strategy concurrently with the climate work on ICT, and the background report (Ramboll) prepared in the former has also informed the latter.

Other initiatives with an emphasis on the ICT sector's climate aspects have also been going on in Finland at the same time as the work on this climate and environmental strategy for the ICT sector. The studies financed by the Finnish Innovation Fund Sitra within its ambit and the assessments of the ICT sector included in the Technology Industries of Finland's low-carbon roadmap have provided additional momentum to the examination of ICT sector impacts in Finland. The Climate Leadership Coalition,

[6] https://valtioneuvosto.fi/hanke?tunnus=LVM033:00/2019

bringing together businesses and other actors for joint climate action, has also been active in this field. At the Government level, a project to promote digitalisation (Ministry of Finance) is running concurrently with the work on the climate and environmental strategy for the ICT sector.

The new 2019–2024 European Commission has drawn attention to the potential and challenges of the ICT sector. These, as well as ICT sector climate and environmental initiatives in certain European countries, the information on which was provided by the relevant Finnish missions abroad, are examined below.

1.2 ICT sector climate and environmental initiatives in the EU and reference countries

In the international arena, the focus in examining the climate and environmental impacts of the ICT sector has to date mainly been on the potential of digitalisation to deliver emission reductions. The topic has garnered increasing interest in the European Union. The current European Commission has issued strategies and initiatives addressing climate and environmental impacts from a number of perspectives. The ICT sector's climate and environmental impacts have gained attention also in other countries.

This chapter highlights examples of green initiatives in countries similar to Finland in terms of digital development as well as in the European Union. The reference countries selected are Sweden, Norway and Denmark, all of which closely resemble Finland in terms of structure of society and legislation. The initiatives of three major European countries – Germany, France and the UK – are also reviewed. The climate and environmental impacts of the ICT sector have been extensively discussed in Germany in particular.

<u>European Union</u>

The European Green Deal[7] adopted by the European Commission on 11 December 2019 includes legislative initiatives to promote the EU objective of climate neutrality by 2050. Initiatives announced in connection with the Green Deal and relevant to the ICT sector include the Industrial Strategy (3/2020), the Circular Economy Action Plan (3/2020), the reform of legislation on batteries and accumulators (10/2020) and the

[7] COM(2019) 640 final: The European Green Deal.

strategy for sustainable and smart mobility (2020). The Commission emphasises that while digital technologies serve as enablers of emission reductions, the sustainability of the sector itself must also be ensured.

The Circular Economy Action Plan adopted by the Commission in March 2020 focuses on resource-intensive sectors, with electronics as one of its priority areas. A key element of the Action Plan is sustainable product policy, in which area a Commission proposal to extend and review the Ecodesign Directive (2009/125/EC) is forthcoming. Sustainability principles, such as environmental footprint, restriction of single-use products and ban on the destruction of unsold durable goods, will also be determined for products.

The aim is to develop tools to increase consumer awareness of products and their lifecycles already at the time of purchase. Consumers will be provided with the right to have products repaired and to obtain spare parts and updates. The Commission will propose minimum mandatory criteria for Green Public Procurement (GPP), in addition to which compulsory reporting to monitor the uptake of GPP will be phased in. The Commission will also introduce a Circular Electronics Initiative[8] mobilising both new and existing instruments to extend the lifespan of electronics devices.

The EU digital strategy supports the Green Deal communication in the pursuit of climate neutrality. The digital strategy, in tandem with the Circular Economy Action Plan, seeks to ensure that devices are designed for durability, maintenance and reuse. Consumers should have the right to have devices repaired and updated in order to extend the lifecycle of the device. The strategy seeks to develop initiatives to achieve climate-neutral, highly energy-efficient and sustainable data centres by 2030. A further aim is to develop transparency measures for telecommunications operators on their environmental footprint.

In connection with its digital strategy, the European Commission also adopted a data strategy[9] designed to create a single market for data within which data can freely roam between sectors and countries. The single market for data is also intended to further the achievement of environmental and climate goals. The Common European Green Deal data space that is a part of the data strategy is designed to optimise the use of data in achieving the objectives of the European Green Deal.

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[8] European Commission 2020: Shaping Europe’s Digital Future.
[9] COM(2020) 66 final: A European strategy for data.

Action to stimulate the EU economy towards recovery from the crisis ensuing from the COVID-19 pandemic is currently under preparation, and it is planned to focus on promoting digitalisation and the transition to a climate-neutral society.

Norway

To date, no specific strategy work focusing on the climate and environmental impacts of the ICT sector has taken place in Norway. In 2016, the Government of Norway adopted a digital transformation strategy stating that the ICT sector offers important opportunities to help reduce greenhouse gas emissions.[10]

Energy consumption in the sector has also seen little examination. The Norwegian Government's data centre strategy[11] states that emissions resulting from the high energy consumption of data centres can be reduced by using electricity from renewable sources. Norway derives more than 90% of its electricity from hydropower. Norway's main attractions as a data centre destination are indeed its renewable energy production and its cold climate. In Norway, the media have also focused on the zero-emission quality of electricity rather than on reining in energy consumption.

Sweden

So far, Sweden has not prepared nor is planning to prepare a national strategy focusing solely on the climate and environmental aspects of the ICT sector. The sector has received some coverage in Sweden's climate programmes.

The Swedish Environmental Protection Agency (Naturvårdsverket) has issued a theme report relating to digitalisation which also addresses means by which the ICT sector could further the achievement of climate and environmental goals.[12] The report provides examples from the fields of production, energy, mobility and consumption. The Government's Fossil Free Sweden initiative also involves the preparation of sector-specific roadmaps, one of which concerns the digitalisation consultancy industry.[13] The roadmap defines targets relating to the sector's energy consumption and emissions and proposes measures to further environmental goals through digitalisation.

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[10] Norwegian Ministry of Local Government and Modernisation 2016: Digital agenda for Norway in brief.
[11] Ministry of Trade, Industry and Fisheries 2018: Powered by Nature - Norway as a data centre nation.
[12] Naturvårdsverket 2019: Digitalisering och miljömålen [ICT and Environmental Objectives].
[13] Fossil Free Sweden 2018: Roadmap for Fossil-Free Competitiveness – The Digitalisation Consultancy Industry.

Sweden has promoted the utilisation of waste heat from data centres. Launched in 2017, Stockholm Data Parks is a joint project of the City of Stockholm and local district heating, electricity distribution and fibre optic cable operators to utilise the waste heat from data centres in the district heating network. The City of Stockholm aims to supply 10% of the city's residential heating demand through recovered excess heat from data centres connected to the city's district heating network.[14] Three new data centres under construction are estimated to be capable of providing heating for at least 35,000 homes.[15] At present, 10,000 homes are heated with excess heat recovered from data centres. Waste heat recovery has also been studied in Luleå.[16]

In the business arena, Ericsson has studied the climate impacts of digitalisation for more than 20 years and published a number of reports on the topic, most recently a theme report on assessing the carbon footprint of the ICT sector[17] and a related broader background report[18].

Denmark

Denmark was an early starter in ICT-related climate and environmental efforts. An Action Plan for Green IT in Denmark[19] was published in 2008. It presented both green initiatives to increase the friendliness of the IT sector to climate and the environment and tools with which IT solutions could make an impact in other sectors. Since the publication of the plan, the topic has attracted less attention, however.

In 2019, the Parliament of Denmark adopted an ambitious new climate bill aimed at cutting greenhouse gas emissions by 70%.[20] The concrete measures to achieve the emissions targets are to be presented in an upcoming action plan that is to cover also the IT sector.

In the context of the climate bill, the Government designated 13 partner sectors which have each issued recommendations for reducing emissions in their sector. One of these sectors is services, IT and consultancy. In addition to the enhanced energy efficiency enabled by digitalisation, the IT sector recommendations also include proposals on harmonising data on environmental impacts and increasing

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[14] https://stockholmdataparks.com/benefits-of-green-computing-in-stockholm/
[15] https://www.datacenterdynamics.com/en/news/stockholm-data-parks-announces-three-new-facilities/
[16] https://www.ri.se/sv/vad-vi-gor/projekt/datacenter-vaxthusodling
[17] Ericsson 2020: A quick guide to your digital carbon footprint.
[18] Ericsson 2020: Background report to 'A guide to your digital climate impact'.
[19] Ministry of Science, Technology and Innovation 2008: Action Plan for Green IT in Denmark.
[20] Ministry of Climate, Energy and Utilities 2019: Forslag til Lov om klima [Proposal for a Climate Act].

transparency, regard to environmental considerations in public procurement, and data centre waste heat recovery.[21]

Germany

The climate and environmental impacts of the ICT sector have been widely discussed in Germany. In March 2020, the German Federal Environment Ministry (BMU) launched the Digital Policy Agenda for the Environment[22], which elaborates on earlier strategies[23] and aims to harness digitalisation to serve the environment, nature and climate. The Agenda emphasises how digitalisation is the only path to accomplish sustainable growth and also focuses on the environmental footprint of the ICT sector itself. The Agenda consists of more than 70 measures. In addition to national initiatives, Germany also supports the development of common EU-wide environmental standards. The environmental aspects of ICT are to be an area of emphasis in Germany's EU Presidency in autumn 2020 as well.[24]

Environmental issues also play a role in Germany's national artificial intelligence (AI) strategy, which includes support to ventures that aid in the achievement of environmental and climate goals and foster climate-friendly digitalisation.[25]

Since 2008, the German Federal Government has applied in its activities a green IT programme aiming to reduce ICT-related energy consumption in federal administration. Under the programme, all ministries are committed to three targets: energy-efficient data centres, sustainable hardware procurement and the Blue Angel environmental label.[26] The Blue Angel environmental label may be awarded to products that take into account environmental and health impacts across the product's entire lifecycle. Label criteria have been determined for products including electronics, data centres and application software. The Federal Government also has in place a programme to enhance the efficiency of materials usage. The updated version, to be

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[21] Regeringens klimapartnerskaber 2020 [Government's climate partnerships 2020]: Service, IT og rådgivning [Services, IT and consulting].
[22] BMU 2020: Digital Policy Agenda for the Environment.
[23] BMU 2019: Get the Environment into those Algorithms! The BMU's key points for a digital policy agenda for the environment.
[24] https://www.bmu.de/en/topics/sustainability-international/digitalisation-and-the-environment/sustainable-digital-transformation/
[25] https://www.bmu.de/en/topics/sustainability-international/digitalisation-and-the-environment/our-support-programme-for-artificial-intelligence/
[26] https://www.bmu.de/en/topics/sustainability-international/digitalisation-and-the-environment/sustainable-digital-transformation/

published in spring 2020, will examine ICT benefits in transforming production towards greater resource efficiency.[27]

The Blue Angel criteria for data centres[28] seek to increase the efficiency of data centres and to ensure that environmental considerations are taken into account also in future investments. The criteria lay down requirements both for buildings and IT hardware. Energy efficiency must be measured and reported according to the requirements, and the data centre must moreover use energy from either renewable sources or combined heat and power plants. Data centres must also have a long-term strategy for increasing their energy and resource efficiency.

The Blue Angel environmental label for software products is designed to encourage energy consumption reductions and increased resource efficiency in the ICT sector. The criteria set for software products[29] mainly concern application software that is primarily run on desktop systems. In the context of the upcoming update, the criteria are to be expanded to apply also to other architectures, such as mobile apps. In order to be awarded the label, the software solution must be energy efficient and make efficient use of device resources.

France

France has recognised the climate and environmental challenges of the ICT sector but has adopted no national strategy on the topic.[30] However, the ICT sector is taken into account in the new French anti-waste law for a circular economy adopted in February 2020. The law aims to promote climate-friendly practices, for example through provisions that require manufacturers to provide consumers with more information on the environmental impacts, lifecycle and repairability of products.

As from January 2022, internet service providers and mobile operators must publicly report the quantity of data consumed and the ensuing greenhouse gas emissions. The aim is to raise consumer awareness of the climate and environmental impacts of

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[27] https://www.bmu.de/en/topics/economy-products-resources-tourism/resource-efficiency/overview-of-german-resource-efficiency-programme-progress/
[28] Blue Angel – The Environmental Label 2019: Energy Efficient Data Center Operation, Basic Award Criteria.
[29] Blue Angel – The Environmental Label 2020: Resource and Energy-Efficient Software Products, Basic Award Criteria.
[30] Since the original Interim report was drafted in Finnish, French Digital Council has published an Environment and Digital transformation roadmap (Conseil national du numérique: Feuille de route sur l'environnement et le numérique, July 2020). The roadmap introduces 50 measures for sustainable technology and ecological digital transition that is aligned with the UN Sustainable Development Goals.

consumption so that consumers can assess the impacts of their own activities and their own digital consumption.[31]

The new law also introduces regulations concerning the repairability of electronics with the aim of providing consumers with more information in support of their purchase decisions and also encouraging producers to make their products better repairable. Product labelling will be introduced in 2021 to rate electronics for their ease of repair and lifespan on a scale of 1 to 10. The labelling applies to a wide range of electronics, including smart phones, computers and televisions. Producers must also disclose the details of the labelling, i.e. the grounds for the product's rating. The law additionally imposes obligations relating to the availability and deliveries of spare parts.

United Kingdom

To date, the climate and environmental work involving the ICT sector in the UK has focused on central government. A Greening Government ICT Strategy was drafted in 2011 as a part of the overall government ICT strategy.[32] Annual reports addressing the measures implemented in central government in the report period and listing tools for future achievement of the targets have been published in connection with the strategy. The sustainable technology strategy 2020[33], an updated version of the Greening Government ICT strategy, was published in 2018.

Steps have also been taken to extend the guidance to the private sector. The Department for Environment, Food and Rural Affairs issued guidelines for a sustainable ICT sector in 2019.[34] The guidelines address the challenges and opportunities of the ICT sector relating to sustainable development and provide recommendations for more sustainable ICT.

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[31] https://www.ecologique-solidaire.gouv.fr/sites/default/files/DP%20Loi%20anti-gaspillage.pdf
[32] HM Government 2011: Greening Government: ICT Strategy.
[33] Department for Environment, Food & Rural Affairs 2018: The greening government: sustainable technology strategy 2020 – sustainable technology for sustainable government.
[34] Department for Environment, Food & Rural Affairs 2019: Helping businesses create greener, more sustainable future through ICT.

2 Key climate and environmental issues in the ICT sector and scope of strategy work

2.1 Digitalisation and the data economy

Digitalisation is shaping society on a global scale. The use of ICT is growing increasingly prevalent, and new applications are being introduced in more and more industries. The aim of the digitalisation of services is to improve lives, business performance or the functioning of society, or to increase the efficiency of governmental decision-making. Digitalisation manifests in the increasing range of digital public services, for example.

Finland is among the world leaders in digitalisation. The EU uses the Digital Economy and Society Index (DESI) to measure the availability of fast broadband internet access, the population's digital skills and internet use, the integration of digital technology by businesses and digital public services, and ICT research and development. Along with Sweden, Denmark and the Netherlands, Finland consistently scores high on the index and was ranked as number one in 2019. The leading EU countries, Finland among them, also rated very well in the International Digital Economy and Society Index (I-DESI) which includes also non-EU countries (such as South Korea, Iceland, Norway and the United States).[35]

The ICT sector, i.e. the manufacture of computers, electronics and optical products, telecommunications and data processing services, accounted for around 5.8% of Finland's GDP in 2018.[36] In 2018, Finland ranked the highest among all EU Member States in the share of ICT experts (7.2%) of the total employed workforce.[37]

The services provided by the ICT sector are changing the ways people interact as well as processes in a wide range of industries. A few decades ago, few could imagine the extent of the changes in the way we work and play brought about by mobile communication and digital services. Similarly, we cannot as yet know how virtual and augmented reality, voice and gesture controls, the Internet of Things (IoT),

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[35] https://ec.europa.eu/digital-single-market/en/desi https://ec.europa.eu/digital-single-market/en/news/how-digital-europe-compared-other-major-world-economies
[36] https://www.ficom.fi/ict-ala/tilastot/ict-toimiala-ja-bruttokansantuote
[37] https://www.ficom.fi/ict-ala/tilastot/ict-alan-ty%C3%B6lliset-ja-koulutus

blockchains, quantum computing and technologies that are now only emerging will change the ways we do things, or what their externalities might be.

As devices, services and all of society are going online to an increasing extent, huge volumes of data are being accumulated on services, devices, users, businesses and all other elements of society alike. The term used for this is global datafication.[38] Vast investment is made in the storage, processing and analysis of data, and some of the success of current major corporations is based on their ability to collect and capitalise on data and to use it to predict the behaviour of the individual.[39] Digitalisation has led to the emergence of the data economy.

In the data economy, the availability and portability of data are key components of value creation. A few years ago, the European Commission estimated that the value of the EU data economy could rise to EUR 739 billion by 2020. The number of data enterprises would increase by 100,000 to top 350,000, and the number of data workers would rise from six to ten million.[40] The European cloud services market, meanwhile, would be valued at just under EUR 45 billion.[41] It has been suggested that data is no longer a commodity but a form of capital[42] that no longer accumulates as a by-product of other activities but instead is actively collected and acquired from everyone and everywhere to be sold onward and used to enhance the efficiency of organisations' own activities.

Digitalisation and the ensuing data economy interact with other ongoing global trends and are therefore linked also to key global challenges such as climate change and the deterioration of natural environments.

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[38] Brady 2019: The Challenge of Big Data and Data Science. Annual Review of Political Science 22.
[39] Prainsack 2020: The political economy of digital data: introduction to the special issue. Policy Studies.
[40] https://ec.europa.eu/digital-single-market/en/news/final-results-european-data-market-study-measuring-size-and-trends-eu-data-economy
[41] Deloitte (for the European Commission) 2017: Measuring the economic impact of cloud computing in Europe.
[42] Sadowski 2019: When data is capital: Datafication, accumulation, and extraction. Big Data & Society 6.

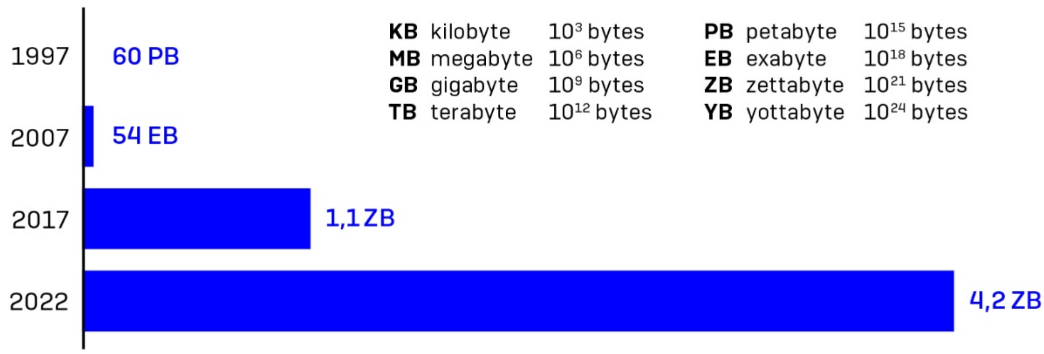
2.2 Role of the ICT sector as source of emissions and provider of solutions to climate challenges

Although perceived as non-material in our everyday lives, digital services involve consuming energy as well as material resources. Digital services rely on the ICT infrastructure, whose construction and use burden the climate and the environment.

Data transmission, processing and storage for various purposes are growing strongly and require server capacity and electrical energy. In Finland, mobile data use in particular has increased significantly, with the current per capita rate being the highest in the world.[43,44]

ICT sector actors and consumers of their services are continuously using new devices. The manufacture of these devices requires energy and materials, including rare earth elements. Raw materials extraction has many direct environmental impacts, such as the degradation and loss of natural environments. It is also a significant source of greenhouse gas emissions. Recycling of materials saves virgin raw materials but is often quite energy intensive and becomes the more challenging the higher the number of materials and the smaller their quantities contained in devices. On the other hand, the ICT sector has improved the energy efficiency of many devices, which has resulted in significant decreases in the in-use energy consumption of devices per data unit.

Figure 1. Global internet traffic is increasing strongly. Source: International Energy Agency (IEA).



[43] Ministry of Transport and Communications 2018: Turning Finland into the world leader in communications networks – Digital Infrastructure Strategy 2025.
[44] https://data.oecd.org/broadband/mobile-broadband-subscriptions.htm

Figure 2. Dozens of times more data per capita is currently transmitted in Finland's mobile networks compared with the early 2010s. Source: Finnish Transport and Communications Agency Traficom.

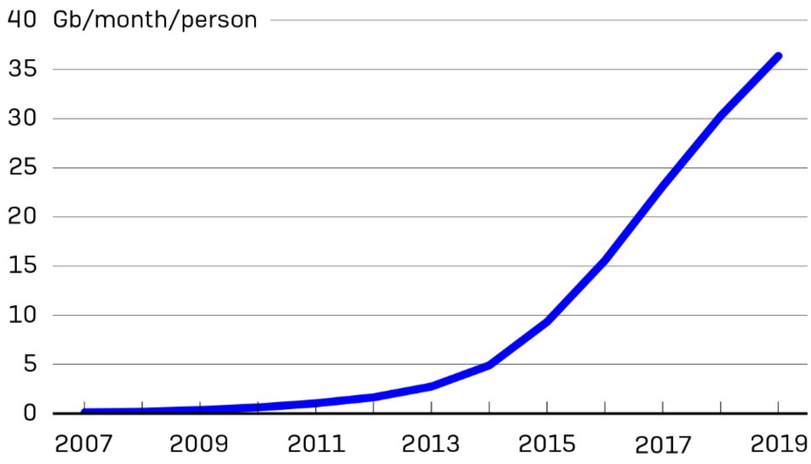
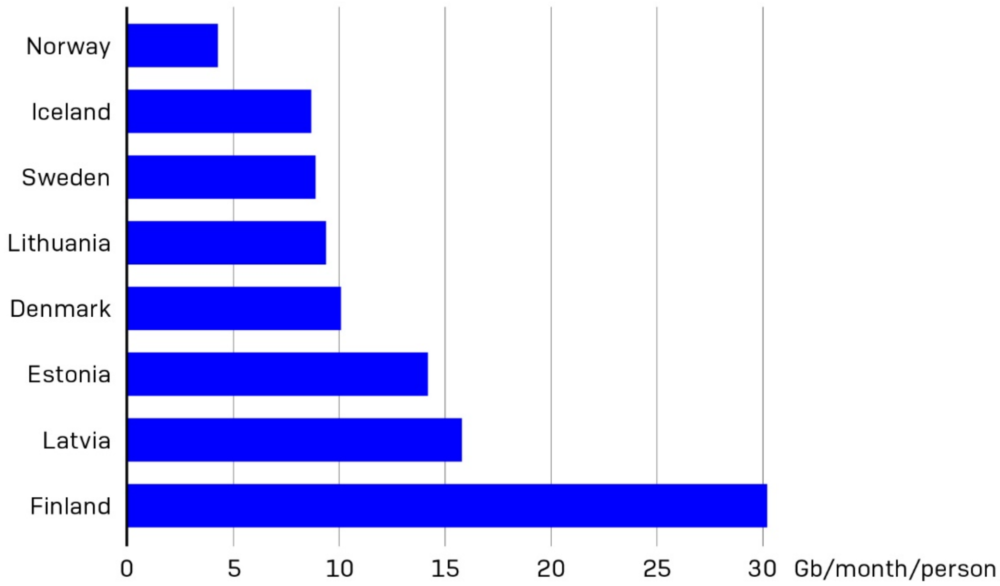
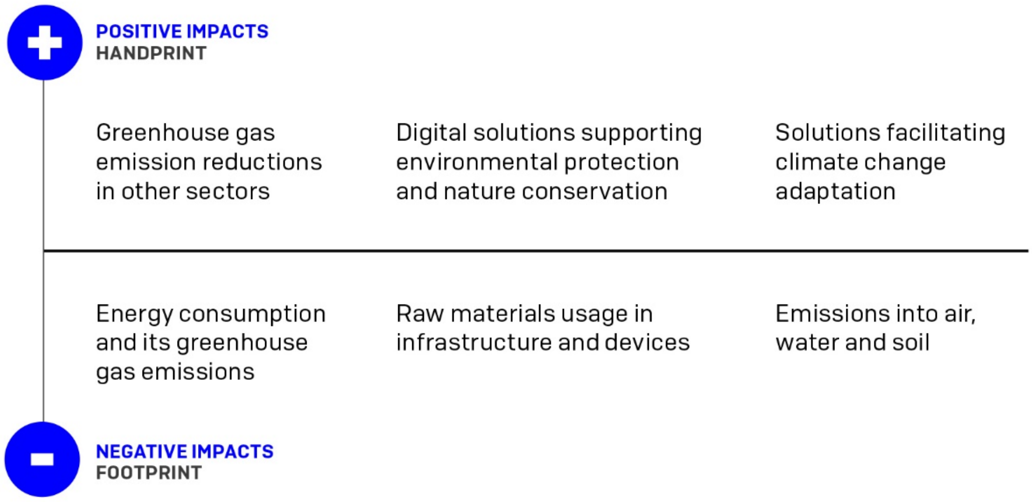


Figure 3. In 2018, the Finnish population was in a league of its own in mobile data use compared with the other Nordic countries and the Baltic States. Source: Finnish Transport and Communications Agency Traficom.



ICT solutions have major potential for enabling reductions in the carbon footprints of other sectors. Through developments such as optimisation, ICT can help lower energy consumption in various industrial processes, replace physical products, facilitate the creation of urban infrastructure that is more resource efficient and has a smaller carbon footprint, and boost a broader economic transition towards a circular economy where resources are utilised more sustainably. The sector may also produce solutions for environmental protection, nature conservation and climate change adaptation, such as better preparedness for flood and wildfire risks.

Figure 4. The ICT sector consumes energy and materials, but its role and potential in response to climate and environmental challenges are also significant.



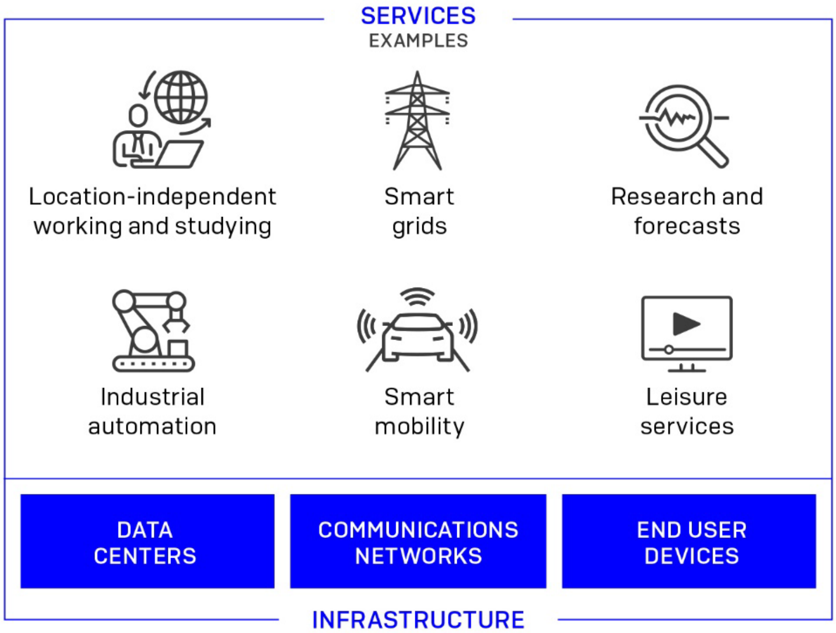
2.2.1 Scope of strategy work

The strategy covers Finland but, where relevant, international examples and studies are also used. This is only natural due to the transboundary nature of the sector. The following groupings and coverages are employed when examining the ICT infrastructure and services provided using it.

Infrastructure comprises data centres, communication networks and end user devices. Chapters 3, 4 and 5 of this report discuss key climate and environmental issues relating to these as well as ways of reducing adverse impacts. Chapter 6 examines the role of software.

The main focus of this report is on energy consumption and material flows, which in previous studies have been identified as the ICT sector’s most significant environmental impacts. Construction-related issues are also covered, particularly as regards networks. The construction of large data centres usually requires an environmental permit issued by a Regional State Administrative Agency, which takes into account matters such as air, water and noise emissions. These topics are examined briefly in the section on data centres.

Figure 5. ICT infrastructure – data centres, communication networks and terminal devices – is used to provide services for the various sectors of society. Many of these services create opportunities for reducing the burden on climate and the environment.



The ICT sector is transforming rapidly thanks to evolving technology. New technologies may result in strong increases in the sector's energy consumption and require material inputs. Applications based on new technologies may also bring forward entirely new solutions to challenging climate and environmental problems. Key emerging technologies and their climate and environmental aspects are discussed in chapter 7.

Benefits offered by ICT in climate and environmental contexts are described in chapter 8. The literature contains different assessments concerning the positive overall impacts ICT can offer in various sectors to curb climate change. The biggest sources of anthropogenic greenhouse gas emissions are energy production and transport that use fossil fuels. Therefore, a decision was made to examine more closely the emission reduction opportunities offered by ICT in the logistics and energy sectors (chapter 9).

At the very outset, it was decided to exclude from the scope of the strategy the impacts of climate change on the ICT sector, such as the impacts of extreme weather phenomena on network implementation or reliability, impacts of the ICT sector on human health and life quality, and the climate and environmental impacts of content production such as the making of videos or podcasts. It was also decided not to consider changes in the number of digital service users. This is why no projection is provided concerning the percentage of the population using these services in the future.

The November 2019 kick-off meeting of the strategy working group also decided that the strategy work would not cover the impacts of any major/sudden societal change on, for example, services used. This scoping proved to be surprisingly relevant in early 2020. On 17 March 2020, powers laid down in the Emergency Powers Act were adopted in Finland to protect the population from the COVID-19 pandemic. The ensuing broad-scale physical distancing measures taken due to the risk of infection resulted in a massive decrease in movement and in attendance of school, studies, work as well as various transactions being largely replaced by solutions utilising digital telecommunications connections. The ICT sector played an important role in enabling society's basic functions under the emergency conditions. It is, however, premature to draw conclusions based on the exceptional situation on any broader switch to location-independent working or on physical mobility being more permanently replaced by digital solutions.

2.2.2 ICT sector and use of electrical energy

Digitalisation is part of the development where more and more of the energy used in society is consumed as electricity. Electrification is necessary for an exit from fossil fuels that accelerate climate change. The fact that electricity generates zero emissions in the use phase also has a positive impact on the air quality of people's local environment. While digitalisation boosts operational efficiency, the electrification of the various systems increases demand for electricity.

Depending on their initial assumptions and scope definitions, different analyses and studies have yielded diverging results concerning the amount, development and distribution of electricity consumption attributable to the ICT sector. According to some reports, electricity consumption occurs particularly in data centres and networks, with end user devices accounting for a somewhat smaller share[45], while other reports emphasise the role of consumer devices[46].

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[45] Morley et al. 2018: Digitalisation, energy and data demand: The impact of Internet traffic on overall and peak electricity consumption. Energy Research & Social Science 38.
[46] Malmodin & Lunden 2018: The Energy and Carbon Footprint of the Global ICT and E&M Sectors 2010–2015. Sustainability.

Research articles published in recent years have estimated that the sector's electricity consumption accounts for around 7–10% of global energy consumption.[42,47,48] The sector's greenhouse gas emissions account for a smaller share of the global total than its electricity consumption, with global greenhouse gas emissions from the sector estimated at no more than 3–5%.[44,49]

Different projections have been made as to future developments. Digital services and their users, devices connected to networks and data intensity of services are all experiencing sharp growth. According to some estimates, the sector's energy consumption might multiply over the next decade.[50] The ICT sector has been capable of continuously improving the energy efficiency of devices and technologies and, so far, the amount of ICT sector energy use has not increased proportionally to the volume of data. Many also expect that, going forward, advances in energy efficiency will continue to be able to respond to the growing demand.[51,52]

There are very few country-specific reports on the sector-wide energy consumption of ICT. Some partial estimates have been conducted in Germany. A study by ETLA Economic Research on ICT and its energy consumption and its trend in Finland was commissioned by the Finnish Innovation Fund Sitra in spring 2020. Prepared under coordination by the Ministry of Economic Affairs and Employment, the low-carbon roadmap of Technology Industries of Finland examines the ICT sector as a single cluster with the service sector and presents scenarios for trends in the sector's electricity consumption and emissions.

The Sitra-funded ETLA study[53] examines the sector's electricity use on the basis of the Standard Industrial Classification of Statistics Finland. According to the study, in 2017 industries within the information sector[54] consumed less than 1 TWh (around 1% of Finland's total consumption of electricity). The figure does not include the electricity consumption of other sectors relating to the use and maintenance of ICT networks

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[47] Andrae 2020: Hypotheses for primary energy use, electricity use and CO_2 emissions of global computing and its shares of the total between 2020 and 2030. WSEAS Transactions on power systems.
[48] Jones 2018: How to Stop Data Centers from Gobbling up the World's Electricity. Nature 561.
[49] Belkhir & Elmeligi 2018: Assessing ICT global emissions footprint. Trends to 2040 & recommendations. Journal of Cleaner Production.
[50] Andrae & Edler 2015: On Global Electricity Usage of Communication Technology: Trends to 2030.
[51] Ericsson 2020. A quick guide to your digital footprint.
[52] Masanet et al. 2020: Recalibrating global data center energy-use estimates. Science 28.
[53] Hiekkanen, Seppälä & Ylhäinen 2020: Informaatiosektorin energian- ja sähkönkäyttö Suomessa. [Energy and Electricity Consumption of the ICT sector in Finland] ETLA Report No. 104, draft 19 May 2020.
[54] Standard Industrial Classification TOL 26 Manufacture of computer, electronic and optical products, 58–63 Information and communication.

and devices. The electricity consumption of consumers’ home use of ICT devices is also excluded from the examination.

The low-carbon roadmap report (15 May 2020 version) produced by AFRY (formerly Pöyry) for Technology Industries of Finland examines ICT particularly as regards data centres and communication networks. The three scenarios provided in the report examine the outlook of the sector’s electricity consumption and emissions, which depends on the sector’s technology transformations for improved energy efficiency and on developments in specific emissions from electricity consumed (see also subsection 2.2.3). The examination expects growth in the ICT sector’s turnover, data centre capacity and data transmission volume to continue at the current rate.

All in all, ICT accounts for a small percentage of both the greenhouse gas emissions and the energy consumption of the technology industry. Among the technology industry sectors, steel and metal producers emit the largest quantities of greenhouse gases and also account for the bulk of the industry’s energy consumption. According to the scenarios examined by the AFRY/Technology Industries of Finland report, the ICT sector’s annual electricity consumption would increase from around 2 TWh in 2020 (around 2% of Finland’s electricity consumption) to around 5 TWh by 2050.

If end user devices were included in the projections in the AFRY report, this figure could be very roughly estimated to be twice as high[55]. This would mean around 4 TWh, which is less than 5% of Finland’s total consumption of electricity. The figure should be regarded as indicative only, however.

The AFRY report has identified multiple ways of curbing energy consumption in data centres in the ICT sector in general, such as the dimensioning of data centres and optimisation of server capacity as well as the use of energy-efficient data transmission solutions and artificial intelligence algorithms. Developing these, however, requires significant research and development inputs.

The ICT sector is linked to electricity production and, more broadly, to energy production not only as an electricity user but also as an enabler of the optimisation of energy use. Wind and solar power output varies depending on external conditions (wind speed, cloud cover, daylight hours), and the increase in the share of wind and solar power production therefore makes it challenging to maintain balance in the power system and requires demand to be adapted to fluctuations in supply. Effective

[55] No precise estimate was produced within the scope of this work. International sources provide figures where terminal device consumption amounts to around 0.5–2 times the total consumption of networks and data centres, depending on the scope of examination.

digital solutions are needed to enable system balancing through demand-side flexibility in the power market. These topics are covered in more detail in section 9.2.

2.2.3 From consumption of electrical energy to greenhouse gas emissions

From the climate change perspective, the crucial question is how the electricity consumed is produced. The carbon emission factor used to convert electricity consumption data into carbon dioxide emissions depends on the power production structure of each country. Globally, fossil fuels still play a major role in electricity production. Around 25% of electricity comes from renewable sources.[56]

In international benchmarking, the electricity consumed in Finland is comparatively carbon-free. A total of 86 TWh of electricity was consumed in Finland in 2019. The sources of electrical energy were as follows: net imports 23%, renewables (hydro, wind, wood-based) 35%, nuclear 27%, fossil fuels 15% (coal and natural gas 11%, peat 3% and waste 1%).[57] As regards lifecycle greenhouse gas emissions, nuclear power is comparable to renewable energy sources[58] and peat to fossil fuels.

Indicative data on the sources of imported electricity can be obtained by examining the power mix of the countries of origin. Electricity is imported to Finland from the Nordic countries (especially Sweden and Norway) and Russia. In Norway (0.2 TWh imported to Finland 2019[59]) and Sweden (16.3 TWh), power production is less based on fossil fuels than in Finland[60,61], whereas Russia (7.5 TWh) generates two thirds of its electricity from fossil fuels. Nuclear power is a common source of electricity in e.g. Russia.[62] Finland also imports some electricity from Estonia but, since Finland exports more electricity to Estonia than it imports from there, the emissions from electricity imported from Estonia do not affect the emissions calculated as originating from Finland.

In addition to improving energy efficiency, enterprises in the ICT sector can reduce their carbon footprint by sourcing carbon-free electricity. For example, the

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[56] https://www.iea.org/commentaries/empowering-electricity-consumers-to-lower-their-carbon-footprint
[57] https://energia.fi/en/news_and_publications/statistics/electricity_statistics
[58] https://ilmasto-opas.fi/fi/ilmastonmuutos/hillinta/-/artikkeli/ed54e5ef-47f6-41b9-bb5d-8d7b72323571/ydinvoima.html
[59] Fingrid 2019: Transmission management.
[60] https://www.ekonomifakta.se/Fakta/Energi/Energibalans-internationellt/Elproduktion-med-fossila-branslen/
[61] https://annualreport2019.fingrid.fi/en/business-operations/power-system/transmission-grid.html
[62] https://www.svkk.fi/venla-2015-2018/uutta-virtaa-uusiutuvasta-energiasta/

sustainability reporting by each of Finland's three largest telecommunications companies includes environmental responsibility disclosures on the entire group's electricity consumption. According to the reports, the electricity sourced by these three actors is mostly carbon free. For more details on the contents of telecommunications companies' environmental responsibility reports, see subsection 4.3.2. The electricity sourcing of telecommunications companies of course has no impact on the direct emissions from electricity consumed by consumer ICT devices or other ICT equipment used outside these companies.

If the renewable electricity purchased by ICT enterprises is produced (under power purchase agreements, PPAs) at plants that otherwise would not be built, such renewable power production can be regarded as additional. For example, Google has entered into long-term PPAs with wind farms to source electricity for its server complex in Hamina, Finland. At least at present, such PPAs require the scale of the operations to be quite extensive, as is the case with hyperscale data centres. Overall, the strong growth in installing additional wind capacity is continuing in Finland due to its cost effectiveness, and the sufficiency of renewable electricity to meet the needs of facilities such as data centres does not appear to pose a challenge.

The low-carbon roadmap report produced by AFRY for Technology Industries of Finland estimates that the Finnish ICT sector's (including data centres and networks) current annual emissions total less than 0.2 Mt of carbon dioxide equivalents, which equates around 3% of the sector's total emissions and less than 0.5% of Finland's total greenhouse gas emissions. Further according to the AFRY estimate, regardless of its robust growth, the ICT sector's emissions will decrease further over the total period until 2050 examined in the roadmap. The report attributes this to the ICT sector's energy efficiency improving through anticipated technological developments, while at the same time specific emissions from electricity used will be approaching zero towards the end of the period.

The total climate impacts of electricity used in each country are determined on the basis of the power production structure – if some industries focus on sourcing green electricity, the power from fossil or other conventional fuel sources will be used by other industries. The increase in electricity consumption in the EU will not, however, result in directly proportional increases in emissions, as power generation is covered by the EU Emissions Trading System. With electrification gaining ground in the various sectors, the question arises as to what the future price of electricity – in particular green electricity – will be. Energy efficiency as a means of curbing growth in total electricity consumption still remains a justified objective. Finland is also committed to the target that the national final energy consumption does not exceed

290 TWh.[63] Over the longer timeframe, the extensive electrification of societies also raises questions concerning limits to the growth of renewable energy and the electrification of society in terms of raw materials, with challenges perceived in aspects such as the sufficiency and location of critical earth elements.[64]

As regards the ICT sector, obtaining an overall picture of emissions from services used within a country is complicated by cross-border data flows and the fact that services used in Finland, too, may activate data centres in countries whose power portfolios are quite different from Finland's.

2.3 Role of consumers

The ICT choices of consumers, businesses and public administration alike make a difference to the climate and environmental impacts of the ICT sector. Consumer behaviour has a considerable effect on the overall picture. In Finland, for example, data transmission generated by private individuals makes up an estimated 90% of all data transmitted in the mobile network.[65] No equally clear and comprehensive understanding of the data transmission volume in the fixed broadband network is available.

In Finland, the volume of data transmitted in the mobile network is high by both European and global comparison.[66] Data transmission volume in the mobile network in the latter half of 2019 amounted to 38 GB per resident. The volume of data transmission is growing at an annual rate of around 20%. However, mobile data transmission breaks down unevenly among users; the average data transmission subscription was used to transmit less than 10 GB per month in autumn 2019.[67]

The high mobile data volume in Finland is explained by factors including the popularity of mobile broadband subscriptions which only include data transmission services and are used by households similarly to fixed broadband subscriptions. Data

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[63] Ministry of Economic Affairs and Employment 2019: Finland's Integrated Energy and Climate Plan.
[64] Viebahn et al. 2015: Assessing the need for critical minerals to shift the German energy system towards a high proportion of renewables. Renewable and Sustainable Energy Reviews 49.
[65] Finnish Transport and Communications Agency Traficom: data collection from major telecommunications companies, spring 2020.
[66] https://tefficient.com/wp-content/uploads/2019/09/tefficient-industry-analysis-3-2019-mobile-data-usage-and-revenue-1H-2019-per-operator-5-Sep.pdf
[67] Finnish Transport and Communications Agency Traficom: Statistics on communications services. Updated 18 March 2020.

transmission over mobile broadband accounted for 56% of all mobile data transmission in autumn 2019. The use of mobile broadband instead of fixed broadband is made possible by the unlimited data included in most subscriptions. At year-end 2019, mobile broadband subscriptions (data-only services) numbered well over 2 million. Nearly 80% of these were used by households and practically all included unlimited data.[68]

Comprehensive mobile access coverage and unlimited data subscriptions have resulted in 41% of Finnish households only having mobile internet access, by means of either a mobile phone or a 4G modem, for example. Slightly over half of households use both fixed broadband and some form of mobile internet access.[69]

The uploading and downloading of video content is estimated to account for around 78% of global IP traffic in 2020 and its share is projected to rise to 82% by 2022. This figure is exclusive of gaming, which in two years' time is estimated to account for 4%.[70] The estimated figure includes video content such as online advertising, the climate and environmental impacts of which have also been assessed[71], yet the majority of the IP traffic most likely consists of consumers' recreational video content distribution. The energy consumption of streaming services is rapidly climbing: Netflix, for example, had a total global energy consumption of 451 GWh in 2019, an increase of 84% on the year before.[72] Although video streaming services in principle produce less emissions than DVDs or Blu-ray discs, digital video streaming services will generate more emissions if streaming considerably overtakes DVD/Blu-ray viewing in popularity.[73,74]

The second largest data transmission source on the internet after video content is online services of various kinds, such as news sites and information services, i.e. traditional web browsing.[75] The actual volume of information on websites has not

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[68] Finnish Transport and Communications Agency Traficom: Statistics on communications services. Updated 18 March 2020.
[69] Finnish Transport and Communications Agency Traficom: Broadband penetration in households. Updated 3 April 2020.
[70] https://www.cisco.com/c/dam/m/en_us/network-intelligence/service-provider/digital-transformation/knowledge-network-webinars/pdfs/1213-business-services-ckn.pdf
[71] E.g. Pärssinen et al., 2018: Environmental impact assessment of online advertising. Environmental Impact Assessment Review 73.
[72] Netflix 2020: Environmental Social Governance 2019 Sustainability Accounting Standards Board (SASB) Report.
[73] Aditya et al. 2019: Environmental Impacts of Shifting from Movie Disc Media to Movie Streaming: Case Study and Sensitivity Analysis. 26th CIRP Life Cycle Engineering (LCE) Conference.
[74] Brennan & Devine 2020: Cost of music. Popular Music.
[75] Http Archive 2020: Time series of Total Kilobytes.

increased to any significant extent, however. The increase in content has rather been driven by website appearance, the number of scripts and advertising.

In Finland, mobile network peak hours fall in the evenings, after office hours.[76] A rapid increase has been seen in the use of video streaming services (e.g. mtv, Ruutu, Yle Areena, Netflix, HBO, Viaplay, Amazon, YouTube). TV programmes or video content are viewed by 84% of consumers on free online services while just under half report that they use paid streaming services. At the same time, around 40% of the Finnish population use internet voice services at least once a week. [77,78]

Social media, instant messaging and internet voice services are most often used on a mobile phone, whereas internet access in the home is more commonly used for TV and movie content viewing and gaming. Both access methods are equally popular for watching short video clips on sites such as YouTube. Altogether 49% of the Finnish population watch TV programmes or movies on the internet at home at least once a week. Around half of them also watch these on their mobile phone. The remainder do not use their mobile phone but only their internet access at home to watch TV programmes or movies.[79,80]

The volume of consumers' video content transmission increases in step with increasing internet usage, which development is made possible by the increasingly better network infrastructure and the rising network capacity. As capacity rises, it is quickly put to use to improve aspects such as image quality. It has been estimated that 66% of the televisions in use globally in 2023 will be capable of displaying high-resolution 4K image.[81] The larger the screen used for viewing and the higher the image resolution, the greater the volume of video content transmission (over broadband networks). Over half of the Finnish population watch TV and video content on a screen of 36" or larger.[82] A telling indicator of the rise in image resolution comes

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[76] VTT Technical Research Centre of Finland: Mobiilimittari.
[77] Finnish Transport and Communications Agency Traficom: Communications services consumer survey 2019. Updated 29 May 2019.
[78] Ministry of Transport and Communications 2018: Turning Finland into the world leader in communications networks – Digital Infrastructure Strategy 2025.
[79] Finnish Transport and Communications Agency Traficom: Communications services consumer survey 2019. Updated 29 May 2019.
[80] Internet access at home may be obtained in the mobile or fixed network, and may also make use of a mobile phone or its network.
[81] https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html
[82] Finnish Transport and Communications Agency Traficom: Communications services consumer survey 2019. Updated 29 May 2019.

from the fact that the number of 4K capable UHD televisions sold in Finland in 2019 increased by 14% on the year before.[83]

All told, the residential energy consumption of Finnish households in 2018 was just under 66 TWh. Devices accounted for slightly under 13% of residential energy consumption.[84,85] Of this, well over nine percentage points went to other electronic devices, which category includes small kitchen appliances, refrigeration appliances, dishwashers, washing machines and tumble dryers, televisions and computers inclusive of peripherals, lifts and car heating. According to an estimate prepared in the UK, computers and other electronic devices account for around 20% of the non-heating electricity consumption of households. Stand-by power on electronic devices alone has been calculated to account for up to 10% of domestic energy consumption.[86] Material flows relating to end user devices and their environmental impacts are examined in chapter 5.

Household consumption in its entirety causes two thirds of Finland's greenhouse gas emissions. The greatest emission sources are mobility, housing and energy, followed by food and other goods and services.[87] The effect on emissions of ICT-related consumption has not been comprehensively analysed in Finland. Different figures are obtained for energy consumption arising from the use of end user devices, for example, depending on whether only the direct consumption of the device or also consumption in networks and data centres is taken into account. The emission factor meanwhile depends on how the traffic required to provide the services is organised. i.e. whether it takes place within Finland.

ICT-related consumption and emissions can vary considerably between individuals depending on the time spent on the device and the devices used (large screens and powerful gaming computers, for example) as well as the networks and data centres used. A Swedish sample calculation puts a person's ICT-related emissions in the range of 0.6–7% of the average private individual's carbon footprint.[88]

Consumers would like to know more about the carbon footprint of ICT services. They are largely unaware of the negative climate and environmental impacts of internet

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[83] http://www.stat.fi/tup/suoluk/suoluk_energia_en.html
[84] http://www.stat.fi/tup/suoluk/suoluk_energia_en.html
[85] http://www.stat.fi/til/asen/2018/asen_2018_2019-11-21_tie_001_en.html
[86] Pothitou et al. 2017: ICT entertainment appliances' impact on domestic electricity consumption. Renewable and Sustainable Energy Reviews.
[87] Nissinen & Savolainen 2019: Julkisten hankintojen ja kotitalouksien kulutuksen hiilijalanjälki ja luonnonvarojen käyttö – ENVIMAT-mallinnuksen tuloksia [Carbon footprint and resource use of public procurement and domestic consumption – findings of ENVIMAT modelling]. Finnish Environment Institute SYKE.
[88] Ericsson 2020: Background report to "A guide to your digital impact".

usage or are aware only of the impacts of end user devices.[89] Regarding Europeans, 28% say that information about the carbon footprint of streaming services, for example, would influence their behaviour. Regarding the Finnish population, the share of those who believe this would influence their behaviour is slightly lower at 24%.[90]

Awareness of sustainable ICT device and service consumption can have an impact on consumer behaviour, because awareness is perceived as putting the matter in the consumer's own hands.[91] On the other hand, the ubiquitous presence of the internet in all aspects of life makes changes in behaviour difficult to accomplish. The negative environmental impacts of internet usage are on the one hand perceived as a matter of immense scale, while on the other hand people are loath to give up the benefits obtained through new technologies. If the measures proposed are perceived as too restrictive, this may bring about scepticism towards the whole thing as well as the effectiveness of the measures.[92]

Consumers also have great faith in the ability of businesses to find new and effective solutions that produce less emissions while maintaining the functionality of the services.[93] This faith in corporate R&D is a significant finding in that the price and ease of acquiring a product or service are important factors that influence consumer choices. In other words, eco-friendlier choices would be easier to make also in the case of ICT devices and services if no extra money or effort was required to locate or acquire these.

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[89] Elgaaied-Gambier et al. 2020: Cutting the Internet's Environmental Footprint: An Analysis of Consumers' Self-Attribution of Responsibility. Journal of Interactive Marketing.

[90] https://ec.europa.eu/commfrontoffice/publicopinion/index.cfm/survey/getsurveydetail/instruments/special/surveyky/2228

[91] Leung 2018: A Study of Perception Factors that Affect Green IT Behavior. Twenty-fourth Americas Conference on Information Systems.

[92] Elgaaied-Gambier et al. 2020: Cutting the Internet's Environmental Footprint: An Analy-sis of Consumers' Self-Attribution of Responsibility. Journal of Interactive Marketing.

[93] Elgaaied-Gambier et al. 2020: Cutting the Internet's Environmental Footprint: An Analysis of Consumers' Self-Attribution of Responsibility. Journal of Interactive Marketing.

3 Data centres

3.1 Data centres and cloud services in Finland

Data centres in Finland are owned and operated by both the private and the public sectors (central and local government, hospital districts). In recent years, the trend has been towards outsourced data centre services and a transition to cloud services in businesses and the public sector alike. In 2012, a report taking into account even the smallest facilities (capacity of less than 0.1 MW) put the number of data centres in Finland as high as 2,800.[94]

The trend of data centre consolidation is associated with the increase in data centre size and the rise of the proportion of private actors among data centre owners and operators. In 2010, the power capacity of data centres across the world was typically 2–5 MW, while today a commonplace figure is 10–50 MW.

Cloudscene, a cloud directory of co-location data centres and cloud service providers, listed 36 privately owned data centres in Finland as at the start of April 2020. In the 2010s, Finland's central government cut the number of its own data centres from 120 to 30, and the number is set to further decline in the near future.[95] Local government often outsources its data centres. This is especially the case in larger cities, and smaller municipalities are also showing increasing interest in switching over to an outsourced service. The underlying reasons include the need for higher and more efficient capacity, the increasingly complex digital environment, and the evolution of the service market.[96] Nonetheless, both the public sector and businesses are likely to continue to retain some data centre capacity under their own control for reasons of information security and security of supply.

Cloud services have quickly risen in popularity in Finland and the other Nordic countries. In 2017, 85% of Finnish businesses and public sector entities used cloud services.[97] Cost savings often provide the incentive for migrating to public or private cloud services, but according to e.g. the Cloud Maturity Index of Tieto (currently TietoEVRY) from 2019, approximately half of the public and private sector actors in

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[94] MarketVisio Gartner, 2012: Konesalit Suomessa 2012 [Data centres in Finland 2012].
[95] Valtori Government ICT Centre.
[96] Association of Finnish Municipalities.
[97] https://www.tieto.com/fi/uutishuone/kaikki-uutiset-ja-tiedotteet/yritysuutiset/2017/06/pilvipalveluissa-on-merkittava-saastopotentiaali-mutta-harva-hyodyntaa-sita-taydella-teholla/

Norway, Sweden and Finland took also environmental aspects, such as energy consumption or carbon dioxide emissions, into consideration in their cloud strategy.

Etla Economic Research[98] illustrates how the increased use of cloud services is reflected in the increase in global IP traffic, which from 2006 to 2011 grew by a factor of seven and from 2011 to 2017 by a factor of four. Businesses have migrated from maintaining their own data centres to cloud architectures. Consumers have likewise switched their service use from end user devices in the home to such cloud architectures. This also entails the transformation of fixed costs (own investments) into variable costs (services). Cloud service models are discussed further in section 6.2.

Table 1: Depending on operating model, a data centre may serve internal or external users or both. Commercial data centre services are provided in Finland by both Finnish and international businesses.

Data centres maintained by actors for their in-house use		Commercial data centres for public and private sector clients	
Public sector data centres	Central government	**Data centres of cloud service providers where servers are owned by the service provider**	
	Local government and regional actors		
Private sector data centres		**Co-location services where the service provider's and the clients' servers are on the same premises**	Telecommunications companies are typical co-location providers, using the data centre capacity for their own needs and also selling it to external clients.

There is no systematically collected and publicly available data on the computing and power capacity or electrical energy consumption of data centres located in Finland. The situation is much the same elsewhere. The electrical energy consumption of data centres is deficiently monitored and details of this consumption are usually kept out of the public eye.[99] At the same time, there is great interest in the energy consumption of data centres and its development, and energy consumption is expected to increase.

[98] Hiekkanen, Seppälä & Ylhäinen 2020: Informaatiosektorin energian- ja sähkönkäyttö Suomessa [Energy and Electricity Consumption of the ICT sector in Finland]. ETLA Report No. 104, draft of 19 May 2020.
[99] Avgerinou et al. 2017: Trends in Data Centre Energy Consumption under the European Code of Conduct for Data Centre Energy Efficiency. Energies.

Andrae[100], for example, recently estimated global data centre electricity consumption to come to around 300 TWh in 2020 and nearly 800 TWh in 2030. Even higher estimates have been put forward.

At the EU level, the European Commission's Joint Research Centre (JRC) has launched the voluntary Code of Conduct for Energy Efficiency in Data Centres initiative to promote the energy efficiency of European data centres and to monitor their energy consumption. The initiative relies on data supplied by the enrolled data centres. In place since 2008, the Code of Conduct has 329 data centre participants, only a few of which are in the Nordic countries. The initiative, although unique, is therefore unable to provide any comprehensive picture.

In 2015, Invest in Finland estimated data centres in Finland to take up around 1% of Finland's electrical energy.[101] This figure is in line with several international estimates on data centres' share of global electricity consumption. If the figure still holds true, in 2019 when total electricity consumption was 86 TWh, data centre consumption would have been 860 GWh. Large data centres of international operators have been taken into use and existing data centres have been expanded in Finland since the estimate made by Invest in Finland.

The Tax Administration publishes annual data on data centres of more than 5 MW because, as of 2014, such centres have belonged to the lower tax category II. In 2019, the energy consumption of data centres of more than 5 MW recorded by the Tax Administration came to 787 GWh. Although there are at least five data centres in Finland having at least a nominal power capacity in excess of 5 MW (e.g. Ficolo, Google, Telia, Yandex) and several operators maintain more than one data centre, the statistics only include those whose available capacity in a single location exceeds 5 MW per year. While the threshold of 5 MW that makes a data centre eligible for the lower tax category is viewed as high by many data centre actors, the power capacity of hyperscale data centres run by international internet companies may exceed this threshold more than ten times over.

In terms of the monitoring and assessment of the environmental impacts of data centres and assessment of the efficacy of possible measures, it is problematic that no statistics on total consumption are compiled on a regular basis. From the viewpoint of data centre operators, details on the electricity consumption of an individual data centre could reveal too much information about their operations to e.g. competitors,

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[100] Andrae 2020: Hypotheses for primary energy use, electricity use and CO2 emissions of global computing and its shares of the total between 2020 and 2030. WSEAS Transactions on power systems.
[101] Invest in Finland 2015: Data Centers in Finland.

and to date no anonymised way has been found to collect data on energy consumption so as to allow the formation and monitoring of the overall picture.

3.2 Design, building and operation of data centres

Data centres have been designed, built and operated in Finland and the world over for decades. The industry is currently undergoing a major transition and the increase in the IT and power capacity of data centres has made them digital processing centres on an industrial scale. In Finland, new industrial-scale data centres are for the most part already connected to the national 110 kV grid.

The design-build-operate (DBO) concept used internationally in respect of data centres is becoming mainstream in Finland as well due to the highly international nature of the industry. The design phase involves determination of objectives relating to matters such as the future data centre’s availability, reliability, security, energy efficiency, automation, scalability, cybersecurity and operation. At the build phase, it is important carefully to implement, introduce and test the key technical systems and to ensure system integration.

The design, building and operation of data centres as a process remains quite fragmented in terms of e.g. maximising energy efficiency and minimising overall cost. Fragmentation adds to the risks of design, building and operation and also increases costs. The most important technical infrastructure in data centres consists of the power distribution system and the UPS and backup power systems (e.g. diesel) that ensure uninterrupted power, along with cooling systems and automation systems. The IT areas with their racks and servers are situated at the core of the data centre’s production process.

3.2.1 Data centre automation

Data centre automation today is accomplished by means of a number of discrete systems that, as a rule, are not integrated into end-to-end solutions to allow real-time monitoring, control, production and energy efficiency. While the technologies and solutions to make this possible already exist,[102] many data centres currently have little

[102] ABB.

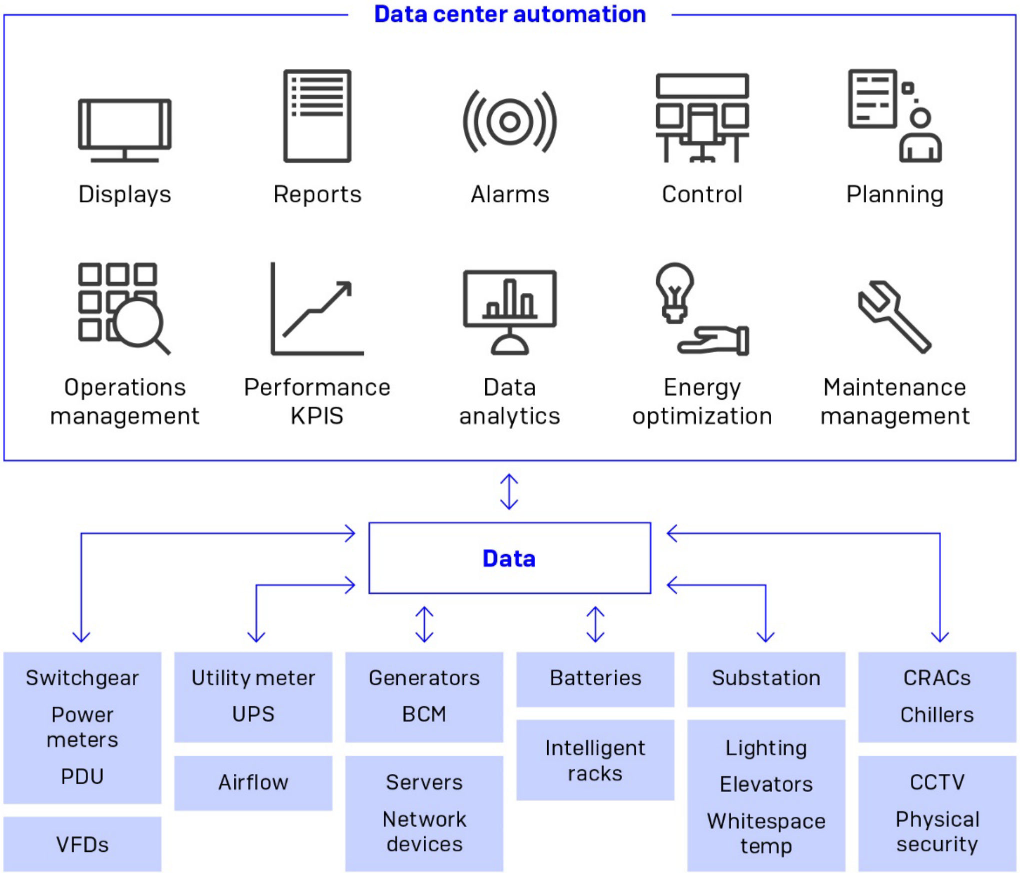
or no energy-use or environmental measurement capability and some do not even have a separate utility meter or bill.[103]

The term generally used for data centre automation is data centre infrastructure management (DCIM). DCIM may refer to a top-level total automation system to monitor and operate all the discrete infrastructures, systems and devices of the data centre, including those relating to IT production. DCIM compiles real-time data on the various subsystems of the data centre, such as energy management, power management, property management, ICT control, security, fire extinguishing and lighting systems, and other systems. Then again, it is also possible to speak of IT DCIM, an infrastructure management system that specifically supports IT production.

Data centre automation systems are used to monitor and control aspects such as the status and settings of the power distribution network, backup power test runs, the condition of UPS battery packs, the condition and operation of the electrical engines and pumps in the cooling system, the operation of cooling compressors, and IT area temperature and humidity. A data centre is a process-critical production facility filled with smart digital equipment and systems. Cybersecurity threats and capabilities must be taken into account at all lifecycle stages.

[103] European Commission 2018: Best Practice Guidelines for the EU Code of Conduct on Data Centre Energy Efficiency.

Figure 6: A data centre consists of multiple discrete systems that in a modern data centre are controlled by means of advanced automation. Source and icons: ABB.



3.3 Energy-efficient data centres

Data centre operations require a large amount of electricity due to the electricity consumption of servers and network devices. The electricity consumption of servers is directly correlated with their data processing capacity. Of the server components, powerful processors in particular consume a significant amount of electricity.

The electrical power consumed in data centres is converted into heat in servers and network devices, and this heat needs to be removed efficiently from server rooms. The consumption, comprising power system losses and energy consumption in the cooling process, results in energy losses in data centres, and efforts are made in energy-efficient data centres to minimise these losses. The price and consumption (MWh/year) of electricity constitutes a significant part of the annual operating costs of data centres, accounting for 40–70% according to various industry sources. It is therefore financially sound to minimise energy losses.

Power Usage/Utilization Effectiveness (PUE) is the indicator commonly used to describe how efficiently data centres use energy. PUE is the ratio of the total amount of electrical energy used by a data centre to the electrical energy used purely by its IT equipment (servers, network and storage devices). A PUE of 1.0 would mean the data centre only uses electricity for IT equipment and not at all for overhead such as cooling. A PUE of 2 would suggest other functions consuming as much electrical energy as the actual IT systems. The IT industry consortium The Green Grid estimated in 2012 that data centre PUEs ranged between 1.1 and 3.0 at that point. PUEs have declined globally in the 2000s, although the trend appears to have flattened in recent years.[104] New data centres can have PUEs of as low as 1.02–1.20.

The most important decisions concerning energy efficiency are made during the design phase. The characteristics and intended uses of the equipment located in data centres as well as the business model (primary and secondary devices alike) play a major role in the implementation of data centre infrastructure. Implementation and, consequently, the achievable energy efficiency is influenced by matters including the following:

- whether the equipment stock consists of a homogenous, virtualised mass of servers or a mix of cus-tomer-owned devices that require co-location facilities;
- whether the servers require a backed-up and disturbance-protected power supply;
- whether the servers contain data that requires specific physical protection;
- in what kinds of conditions the equipment is designed to function;
- on which primary and secondary cooling technology and solutions the data centre is designed to function;
- whether the equipment uses alternating or direct current;
- what kind of power distribution and backup power technology (energy efficiency/losses) is used;
- whether the data centre must be capable of supporting multiple technologies, backup times and security levels;
- whether the data centre is capable of utilising a modern end-to-end automation solution with a real-time combination of all infrastructures, devices and functions that enables energy balance optimisation.

These parameters can be used as a basis for the design of a vast variety of data centre types. In Finland, for example, Google and Yandex have implemented data

[104] https://journal.uptimeinstitute.com/is-pue-actually-going-up/

centres for the cloud service provider's own specific use, whereas Equinix, Telia and Ficolo have co-location facilities. Co-location makes it challenging to achieve the very lowest PUE ratios, and the same applies to the potential recovery of waste heat (see below).

Instead of PUE, other metrics such as Data Centre Workload Power Efficiency (DCWPE) can also be used to calculate energy efficiency.

3.3.1 Data centre power system

A data centre's power system consists of a connection to the power grid, the facility's internal distribution system, conversion to operating voltage, generators securing reliable access to power, UPS devices and batteries ensuring an uninterrupted power supply, and distribution of operating voltage to IT devices in the server rooms. Since a data centre typically aims at an uninterrupted power supply for devices, the above-mentioned structural components are often duplicated to ensure operational reliability and on-line maintenance.

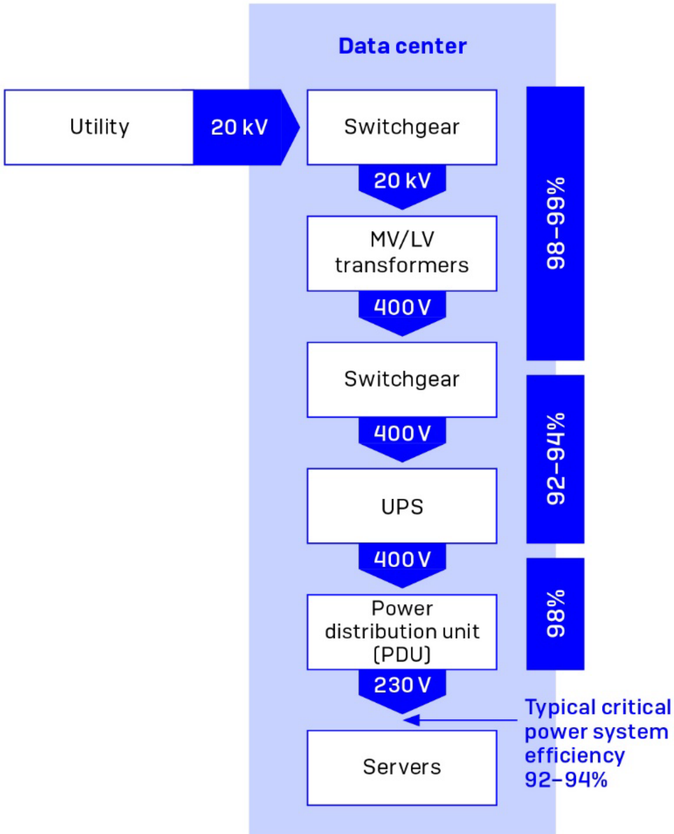
Energy losses always occur in the structural components of the power system due to reasons such as conductor resistance. In the multi-level power distribution system of a data centre, this can be seen as many consecutive energy losses that create an aggregate energy loss of around 10% between the connection to the power utility and the devices consuming electricity in the server room (Figure 7). Duplication (redundancy) means that the full capacity of the devices in the system is never in use and that UPS devices and transformers may operate in a suboptimal power range, increasing energy losses in relation to target values in optimal conditions. Conversions from alternating current (AC) power to direct current (DC) power in UPS units and batteries are not ideal in terms of efficiency, which means that an uninterruptible power supply further reduces the system's efficiency compared with a non-UPS system.

For energy-efficient deployment, the power network components must be selected carefully and dimensioned specifically in relation to the data centre's actual load.

The efficiency of structural components is highly dependent on actual operating power, and efficiency is often particularly low in cases where, for example, a transformer or UPS unit is running below full capacity due to a low actual load. An energy-efficient deployment of equipment such as transformers or UPS units is, however, expensive and, when selecting components, the lifecycle energy savings must be weighed against the higher acquisition cost. Likewise, backup and redundancy must be optimised in the power system to minimise unnecessary energy losses. Any redundant active components always consume energy, and actions such as battery charging cause energy losses. [105,106,107]

Diesel generators are commonly regarded as dependable sources of backup power for data centres. The Finnish power grid is typically so reliable that, in practice, generators are only seldom used to generate electricity for a data centre. Instead, their use is limited to any rare disturbances in the power grid. Consequently, the role of diesel backup power in data centre energy consumption is mostly very small and limited to regular test runs and the management of rare faults. The use of backup power may, however, account for even a significant proportion of a data centre's carbon dioxide emissions.

Figure 7. Energy is lost in the data centre power distribution system.



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105 https://tc0909.ashraetcs.org/documents/ASHRAE_TC0909_Power_White_Paper_22_June_2016_REVISED.pdf
106 https://www.google.com/about/datacenters/efficiency/
107 http://green-data.blogspot.com/2017/12/multimode-UPS-boost-data-center-efficiency.html

3.3.2 Cooling

Data processors typically require an environment where temperature and humidity are controlled. The ASHRAE framework provides a recommended temperature range of 18–27 ºC for air cooling and relative humidity (RH) at 60% for IT equipment spaces. Any significant deviations from the recommended conditions reduce the technical life of devices and increase the risk of failure, reducing operational reliability and cost effectiveness.

ASHRAE has determined several environmental classes, the strictest of which (A1) is the class most commonly used in IT environments. The less stringent classes (A2–C) allow a broader range of e.g. environmental conditions, with lower requirements applying to cooling solutions and therefore enabling better energy efficiency. For example, the network devices, base station equipment and mobile network components used by telecommunications operators typically function within less stringent environmental ranges, enabling more energy-efficient cooling solutions in equipment spaces of the operator's network than in data centres.

Server room cooling is typically the single largest component of a data centre causing energy losses, and therefore efforts are made to optimise cooling. The energy required for removing the thermal load caused by devices from server rooms may amount to10–100% of the energy consumed by the data centre equipment. The following factors have a significant impact on the energy efficiency of the cooling process:

- ambient weather conditions outside the data centre
- server room target temperatures and any deviations
- characteristics of the data centre building
- use of aisle containment in server rooms
- safety and security requirements
- chosen cooling solution.

In Finland, the climate enables the free cooling of data centres, and this is the most commonly used cooling method in the country. In free cooling, external ambient conditions are utilised to chill the cooling air or liquid to the target temperature, typically by using outdoor condensers or available surface water. In cool climates, free cooling can be employed to cool data centre server rooms to the target temperature for as much as 90% of the year.[108] In free cooling, the energy consumption of the cooling process is limited to the circulation of the air or liquid, heat transfer between

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[108] https://en.ilmatieteenlaitos.fi/download-observations

the cooling liquid and air, and the energy required by the condensers. When functioning optimally, the free cooling process only consumes a few per cent of energy in relation to server room payload. The recovery of waste heat instead of channelling it into external air/water is discussed in subsection 3.6.3.

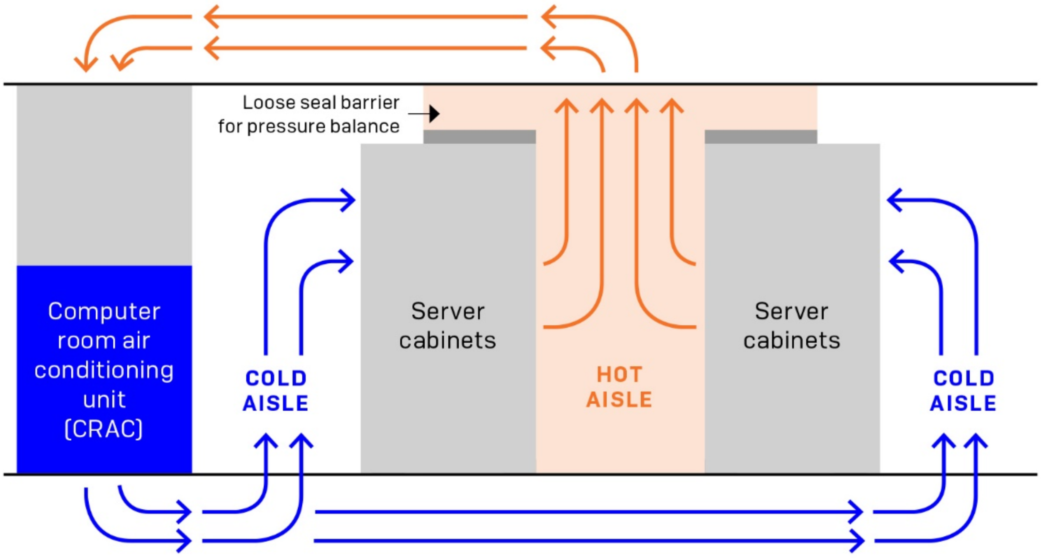
For free cooling to be efficient, the server room target temperature must be quite high. For the most part of the year, it is substantially easier to reach the top end than the bottom end of the above-mentioned ASHRAE recommended range through free cooling by using, for example, cooling based on condensers located in free external air. For example, during 2019 the Helsinki Kaisaniemi observation station of the Finnish Meteorological Institute measured temperatures above 20 ºC for 5.4% of the total annual observation hours and temperatures above the 27 ºC top limit of the ASHRAE recommended range only during 28 hours.

Minimising any obstructions to the circulation of liquid or air in the process also helps improve cooling efficiency. This is affected by the length of the cooling pipe system, the flow rate in the cooling pipe system, the type of pumps used, the size of the ventilation ducts, the obstruction-freedom of server room cooling air routes, the height of server room air space, and the clear separation of cold and hot air (aisle containment) in the server room. Cooling optimisation is most effective if the above factors are taken into account already when designing the data centre building. Good design and identification of final cooling needs during network design is very important to enable correct dimensioning.

Control of cooling air flow within the server room is a key element of energy-efficient data centre implementation. This requires an efficient basic solution in the form of a hot and cold aisle to prevent any uncontrolled mixing of cold and hot air and to channel cooling air to the right place (Figure 8).[109] Device cooling air intake from the cold side of the aisle and the air tightness of device cabinets to prevent leak flows must be controlled through aisle containment and selection of devices in the room.

[109] https://cool-shield.com/aisle-containment

Figure 8. Aisle containment improves the energy efficiency of data centre cooling.



Alongside free cooling, data centres almost invariably also use another cooling system to cover periods when free cooling cannot be used fully or at all due to a reason such as ambient weather conditions. In such cases, compressor-driven water cooling units or close-control units are typically used to support the primary system. Although the energy efficiency of these systems is low, their significance from the perspective of annual energy consumption is rather limited when free cooling is implemented ideally. Data centre automation supports cooling system optimisation.

The safety and security requirements set for the data centre limit the available cooling solutions to some extent. For example, it is not possible to install extensive ventilation ducts in blast-protected areas or gas-proof cave spaces, whereby the range of cooling solutions available is restricted to ones that are based on liquid circulation or powered by electricity.

3.3.3 Other energy consumption

The electricity consumption of a data centre is affected by the facility's lighting, heating, ventilation, maintenance as well as control room and office work. Owing to the energy intensity of server infrastructure, these components play a relatively small role within the whole system and can for their part be minimised with available technical solutions.

3.4 Other environmental impacts of data centres

Those data centres in Finland that fall within the scope of application of the Environmental Protection Act (527/2014) (activity that poses a risk of environmental degradation) require not only a building permit but also an environmental permit. During environmental permit consideration, the matters examined include the following, although the focus of the examination ultimately depends on the volume of the data centre's operations, its location, cooling and backup power solutions and other aspects:

- air emissions from diesel generators
- storage and loading of generator fuel and any other chemicals
- water use and sewerage
- noise
- transport
- waste, incl. hazardous waste such as heavy metals and oils
- impacts on soil and groundwater
- impacts of a water-cooled data centre on the receiving water bodies.

In practice, permit regulations are issued particularly on the storage and treatment of waste and hazardous substances and on generator emission limits and, in the case of water-cooled data centres, the conveyance of water into water bodies. The thermal input of backup generators and the storage of fuels as well as impacts related to water conveyance are also among the criteria examined when considering the need for an environmental permit.[110] Under the Environmental Protection Act, operators of activities subject to a permit must also ensure and verify that energy is used efficiently in the activities.

Up-to-date and energy-efficient servers play an important role in maintaining the energy efficiency of data centres. However, there is not enough understanding or studies of material flows relating to the upgrading of servers and other devices,[111] and further research would be required to form an overall picture.

There are also a few Finnish examples of data centres built in obsolete factories. The use of areas already in industrial use rather than areas that are closer to their natural

[110] Regional State Administrative Agency of Southern Finland Decision 258/2017/1 Reg. no ESAVI/9910/2016; Regional State Administrative Agency of Southern Finland Decision 159/2013/1 Reg. no ESAVI/230/04.08/2012; Environmental Protection Act (527/2014).
[111] Köhler et al. 2018: Energie- und Ressourcenverbräuche der Digitalisierung. [Energy and resource consumption resulting from digitalisation.] Öko-Institut (Institute for Applied Ecology).

state can in itself be regarded environment-friendly, especially if materials sourced locally are utilised in construction. On the other hand, such properties may be located on sites that are not less than ideal as regards waste heat recovery, as they are far from potential users of the heat.

3.5 Future trajectories

3.5.1 From data centres to edge computing?

The storage and processing of data are projected to change in the future. According to the European strategy for data[112], 80% of the processing and analysis of data today takes place in data centres and centralised computing facilities, and 20% in smart connected objects and in computing facilities close to the user ('edge computing'). The strategy estimates that by 2025 these proportions are likely to be inverted, which would present economic and sustainability advantages and also open up opportunities to increase control over one's own data.

Wireless data transfer – especially 4G/5G, LoRa, LiFi – has introduced, alongside cloud computing, the edge computing that originally was perceived to support computing needs related to the Internet of Things (IoT) in particular but which has been much applied also for more commonplace distributed computing needs.

The focus in research into the utilisation of edge computing has been on improving computing system performance. The aspects typically subject to optimisation have been latency, execution time, reliability and data security. Likely due to the fast pace of other technological development, energy efficiency has long been on the sidelines, with attention starting to be paid only once the energy consumption of (cloud) service systems has increased to become a factor of significance.

With some applications, edge computing may deliver significant energy savings – up to 80%[113] compared to a centralised cloud computing system – but the topologies that deliver these savings are service-specific. Benefits have been obtained when energy efficiency has been adopted as the starting point for design, the ratio of computing to traffic has been optimised in the distributed computing system implemented, and the particulars of the service provided have also been taken into account. No energy-saving solution to meet all needs would appear to be on the horizon. Implementing an

[112] COM(2020) 66 final: A European strategy for data.
[113] E.g. Ming Yan et al. 2019: Modeling of Total Energy Consumption of Mobile Network Services and Applications. MDPI Journal of Energies.

energy-saving computing solution often calls for specialised expertise and time-consuming development.

Edge computing applications drawing on IoT underscore not only the energy consumption of wireless data transfer but also the energy efficiency of sensors and various field/gateway devices relative to the energy efficiency of the computing taking place at data centres. What is also of significance is whether edge computing is operated with battery power or current supply, and whether the energy required can be produced by renewable sources.

Since service-specific implementations are needed to improve energy efficiency, expectations are aimed at systems that focus on the dynamic management of services and resources. Virtual machines provide the mechanisms for distributing services and consequently provide opportunities for energy-efficient service distribution into the sphere of edge computing. The IT industry consortium The Green Grid has raised the need to make use of the Power Usage/Utilization Effectiveness (PUE) approach also in small edge computing centres or edge computing elements. Systems manufacturers integrating into e.g. DCIM systems features that promote energy efficiency could be seen as a natural development.

3.5.2 Quantum computing

With the need for computing capacity continuing to increase, current technologies will at some point be exhausted when it comes to energy efficiency. Quantum computing is viewed as a promising addition to digital technology. While quantum computers are already in limited use, ordinary supercomputers will remain the workhorses of the digital world throughout the current decade. In the long run, however, quantum technologies are vital to combating climate change due to their potential energy efficiency. This will require long-term development in both quantum computer construction and quantum algorithm development (for more on this topic, see chapter 8).

Quantum computers often use superconducting circuits and the computing itself therefore takes very little power. By far the greatest energy consumption arises from the cooling of the quantum computer. At present, quantum computer processors need to be cooled down close to absolute zero (-273 °C). The space that requires cooling is very small, however. Compared to an ordinary server room, only the processor itself requires cooling and not the entire room. Quantum computers themselves generate very little heat, which further reduces the need for cooling. For example, the largest quantum computer of D-Wave Systems, the D-Wave 2000Q, requires 25 kW of power.[114]

In solving the kinds of problems that a computer such as the current D-Wave 2000Q is capable of running, the quantum computer is estimated to require only one hundredth of the energy needed by a digital supercomputer.[115] Since the need for cooling is highly localised, energy consumption may be expected to rise only moderately as the computing power of quantum computers rises. Therefore in future, the computing power of quantum computers per unit of energy will further improve. This may be considered a promising trend especially with regard to computationally demanding problems.

3.6 Tools for the management of climate and environmental impacts of data centres

A description of the range of tools available for the management of environmental and climate impacts of data centres in the context of data centres as users of electrical energy is provided below: 1) mitigating the growth of electricity demand by increasing energy efficiency, 2) emission impacts of the sources of electrical energy used, 3) utilising thermal energy generated by the operation of electrical devices and 4) other tools.

3.6.1 Incentives and barriers to increasing energy efficiency

The technology and expertise needed to implement an energy-efficient data centre are accessible in the market from many suppliers, and there are several reference implementations of energy-efficient facilities available from recent years. Designers, builders, technology suppliers and project leaders in the market have sufficient competence and experience to implement new facilities and to improve the energy efficiency of existing ones. Data centre investments are, however, substantial and their economically viable implementation calls for extensive in-house capacity needs or commercial demand for capacity.

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[114] D-Wave Systems 2020: Practical Quantum Computing - D-Wave Technology Overview.
[115] https://www.top500.org/news/d-wave-intros-2000-qubit-quantum-computer-reveals-first-buyer/

In data centre operations, economies of scale are obvious and the energy-efficient implementation of a large capacity cluster is easier than upgrading multiple small spaces. Industrial-scale commercial data centres and cloud service providers strive, almost without exception, to maximise energy efficiency in order to optimise operating costs and profitability. Correspondingly, in a small data centre either the percentage or the absolute amount of energy costs may be small in relation to the total cost or the investments required to improve energy efficiency.

As a rule, an appropriately implemented large-scale data centre is also more efficient than a facility originally built for some other purpose. Even small data centres typically must be prepared for peak loads and have excess capacity that reduces efficiency. In a large unit, load changes are more statistically predictable and dimensioning excess capacity and keeping it at a reasonable level is accomplished more efficiently than in small units.

Switching from an existing facility to an energy-efficient data centre is typically expensive, which slows down the achievement of energy efficiency. Although the trend is shifting from decentralised small data centres towards more centralised services (see section 3.1), Finland still also has data centres built in the late 1990s and early 2000s whose replacement with energy-efficient facilities would further improve energy efficiency. However, the present strategy work did not involve any more detailed assessments of the number or energy consumption of such data centres/server rooms.

In many industrialised countries, the data centre business is construed as an energy-intensive business and granted tax incentives. In Finland, data centres whose capacity exceeds 5 MW are entitled to the significantly reduced electricity tax rate under category II and therefore benefit from cost reductions, which provides an incentive for large-scale centralisation. In practice, however, the 5 MW limit is high for many data centres (see also section 3.1).

3.6.2 Electricity sources

Climate emissions of data centres are mainly formed by emissions from the production of electrical energy used by the data centres. In the current situation, a large proportion of data centre actors and customer demand for data centres is oriented towards the use of renewable energy sources in order to reduce climate-warming emissions. Data centre operators such as Elisa, Ficolo, Google, Hetzner, Telia and TietoEVRY have announced that they will only source electricity from renewable energy sources for their data centres in Finland.

In practice, the use of renewables takes place by acquiring Guarantees of Origin for electricity from renewable sources at an amount corresponding to the annual amount of electricity consumed. Large actors may also enter into power purchase agreements (PPAs) with companies producing renewable energy, i.e. make a long-term commitment to purchase the capacity of selected power plants (see subsection 2.2.3).

One practical challenge in data centres' direct physical use of renewable energy is that their energy consumption is fairly constant around the clock, whereas the supply of renewable energy is subject to major fluctuations. Google has studied the diurnal availability of carbon-free energy over the course of the year compared with the consumption by its Finnish data centre. According to this study, the availability of carbon-free electricity and the electricity use of data centres match each other for up to 97% of the year (in 2017).[116] In this case, carbon-free electricity comprises the Finnish wind power production under Google's PPAs and, where this is not sufficient, electricity produced for the Finnish power grid from renewable sources of energy and nuclear power.

Efforts can be made to respond to the temporal mismatch between the supply and demand of renewable electricity production by, for example, storing electricity in batteries[117]. Google has developed a demand-side flexibility mechanism for its hyperscale data centres, focusing computing on the hours with the highest availability of carbon-free and renewable energy. The system utilises daily forecasts of power supply fluctuations combined with the company's internal estimates of computing capacity required for each hour.[118]

3.6.3 Waste heat recovery

An operating data centre releases a significant amount of waste heat to the warmed cooling liquid or extract air. This waste heat can typically be evaporated into the surrounding air or a water body through free cooling. Waste heat recovery enables the reuse of energy that has already been used once, and it may reduce the need to use other resources to produce heat. For example, Elisa has calculated that the recovery of waste heat from a single data centre may reduce the annual carbon dioxide emissions from district heat production by 1,300–1,500 tonnes, which would equal the carbon footprint of 130–150 people in Finland.

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[116] Email Devon Swezey/Google, 24 April 2020.
[117] Pärssinen 2019: Towards Sustainable Data Centers and Data Services. Aalto University Publication Series.
[118] https://www.blog.google/inside-google/infrastructure/data-centers-work-harder-sun-shines-wind-blows/

Data centre waste heat can be utilised in the district heating network and can therefore partially replace the use of other energy sources. Waste heat recovery requires 1) the location of the data centre to be close enough to a district heating network, 2) a method for the efficient recovery of waste heat and its conversion into a form usable by the district heating network and 3) a commercial rationale for heat collection and recovery to cover the investments needed. How to utilise the heat during the warm seasons is also one of the challenges.

Waste heat from a data centre is typically air or a coolant at around 30 °C. Depending on the time of year, the district heating network requires water that is around 70–90 °C. The temperature of water injected for waste heat recovery must be increased with a heat pump to a level suitable for the district heating network. Consequently, waste heat recovery in the district heating network requires an investment in a heat pump, which will also consume some additional electricity. On the other hand, the electricity consumption of the data centre's normal cooling system drops when cooling is also provided by the heat pump.

A data centre also always needs an alternative cooling system operating as a backup system for situations where the heat pump is not capable of transferring heat into the district heating network during periods such as heat pump maintenance or other possible downtime. This means that the heat transfer solution described above is not usually sufficient on its own to supplant the need to invest in free cooling or water cooling units. Instead, it requires further investment.

Data centres are a stable and reliable source of heat, making them attractive to district heating companies. The thermal energy created in data centres is in itself cost-free, but its recovery and utilisation call for investments. For waste heat to be utilised economically in a district heating network, it must be cheaper than the thermal energy it replaces.

Waste heat from data centres can also be utilised by channelling the heat into the return pipeline of the district cooling network production plant. With the heat pump of the production plant, the waste heat can be used as an energy source for district heat. The utilisation of district cooling networks in Finland is restricted by the fact that they are only found in a fairly small number of cities and limited areas.

There are positive examples of waste heat recovery from data centres in Finland, but its large-scale potential, which at times also emerges in public debate, can be regarded as being underutilised. Interest in the recovery of the waste heat created in data centres and the economic viability of such utilisation is likely to be increased by the energy tax reform currently discussed in Finland whereby a lower tax category (II) would apply to the electricity used by heat pumps and data centres producing heat for the district heating network.[119]

3.6.4 Other tools

Raising the operating temperature

When the operating temperature of a data centre is raised, the annual free cooling period becomes longer, the mechanical cooling period becomes shorter and, consequently, energy consumption decreases. Although raising the cooling temperature results in an increase in either fan or water pump speed, the energy consumption for this is considerably lower than the energy required for mechanical cooling. A higher temperature also shortens component life, but the impact of this on the benefits available is difficult to determine, as the server replacement rate in large data centres in particular is fairly high in any case.

Raising the operating temperature has become more commonplace, and many of the sector's large players currently run their data centres at higher temperatures. This approach is more useful in climates warmer than Finland's.

Keeping the operating temperature of hot-water cooled systems as high as possible saves cooling circuit energy and reduces condenser and pump energy consumption. This way, waste heat recovery can also take place more cost-effectively, as the temperature of the water piped into the district heating system is already higher.

Direct liquid cooling of processors and electronics

Server solutions using direct liquid cooling have recently been taken into use to a limited extent, especially in applications relating to high performance computing (HPC). Increases in processing power result in increases in data centres' local power density and thermal load.[120] Liquid cooling enables more efficient heat transfer at a higher coolant temperature, which means that even a high outdoor air temperature will not prevent the functioning of free cooling based on liquid circulation. This means free cooling could, in principle, operate around the year without e.g. a compressor backup system.

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[119] https://vnk.fi/documents/10616/20764082/hiilineutraaliuden+tiekartta+03022020+en.pdf
https://vnk.fi/documents/10616/20764082/kestavan+verotuksen+tiekartta+03022020+en.pdf
[120] ASHRAE 2019: Water-Cooled Servers Common Designs, Components, and Processes. White Paper Developed by ASHRAE.

Support for the power grid

A reliable power system of a data centre typically features a significant amount of batteries and generator backup power. This infrastructure is typically only used during power grid incidents to ensure the data centre's reliable access to power. Due to the redundancy requirement, the generator capacity of a large data centre is typically high in proportion to the facility's production load, and a data centre may produce a significant amount of electricity for the power grid rapidly, momentarily or over a longer period of time.

Feeding energy from data centre batteries into the power grid can have a very rapid impact on power grid frequency fluctuations and, consequently, support the functioning of the power grid. Backup power generators can either produce energy for the power grid with a slightly longer time lag or disconnect a significant amount of load from the grid to manage an incident. Data centres with these arrangements can be utilised as support for the power grid and help avoid separate investments in load-following power plants.

Backup generator solutions

Wärtsilä has developed gas-fuelled backup power generators for use instead of diesel-powered ones. The benefits of natural gas compared with diesel are the absence of particulate emissions and the lower carbon dioxide emissions. Biogas is also an option. Backup power systems can also be based on lithium-ion batteries.

3.7 CASE: Super data centre

The biggest climate impact of a data centre built for supercomputers arises from its electricity consumption. Other essential aspects include the materials of the equipment and structures and their recycling. As with data centres in general, the electricity required for system energy supply and cooling is usually also the most expensive component, so optimisation of electricity consumption is sought through design and location choices.

Finland's climate conditions reduce the need for cooling energy in particular. The quantity of waste energy is reduced by outside air and water cooling. Hot water cooling in particular provides an energy-efficient cooling solution where cooling water circulates directly inside supercomputers. If data centres are built in an area with existing district heating infrastructure, heat recovery can also be employed.

In the Finnish city of Kajaani there are currently two fully outside-air and water-cooled data centres intended for supercomputers. The new world-class supercomputer centre to be built in 2021 will have hot water cooling, and its waste heat will be recovered for the district heating network.

The recycling of batteries, cooling systems, switchboards and various types of piping and cables is outsourced to specialised facilities. The reusability of used and ageing computer systems is highly case-dependent. The maximum cost-effective life of the world's top-class supercomputers is around 5–6 years, after which their energy efficiency will be lagging considerably behind new technology.

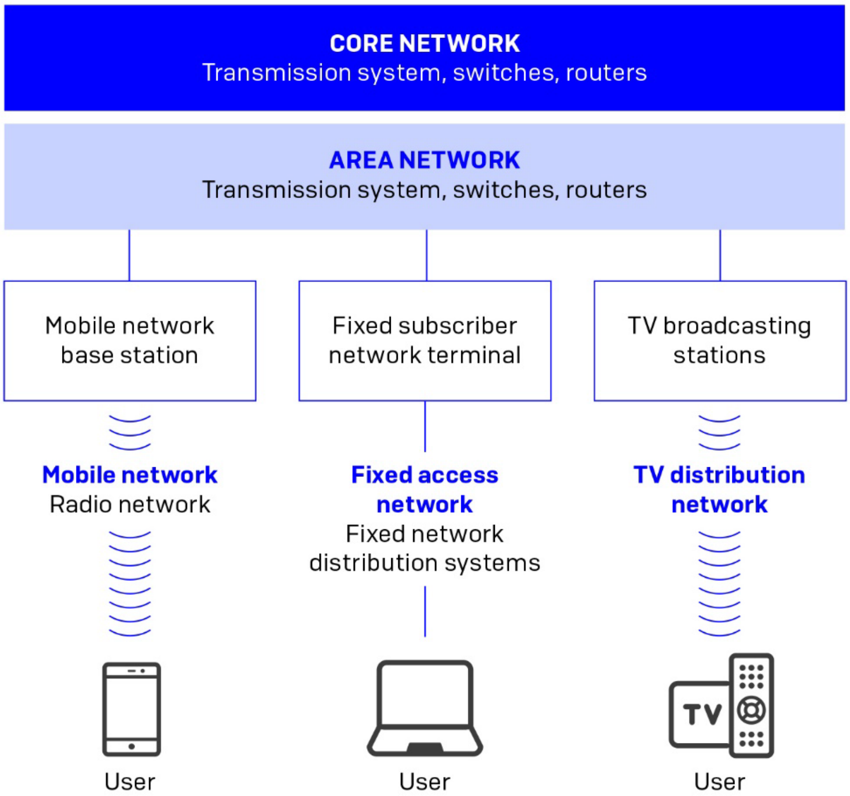
Automation improves data centre functions and processes as well as energy efficiency by optimising the functioning of automation on the basis of data collected. The future will see the improved use of artificial intelligence (AI) and AI data in automation control and equipment lifecycle management. Maintenance plans help ensure device functioning, timely maintenance and device replacements.

4 Networks

4.1 Existing technological solutions

The digitalising society requires communication networks of increasing performance capacity. These consist of connections using either fixed or wireless data transmission as well as various systems that handle the switching and transmission of data. Networks can be divided in many ways, for example according to their regional hierarchy (topology), into internal networks, access networks (subscriber network), area networks and core networks. Networks can also be divided into public and private networks depending on whether they are used to provide communication services to an unrestricted or restricted group of users. Figure 9 shows a diagram of a communication network. It illustrates the networks and their components examined in this chapter from the viewpoint of energy efficiency.

Figure 9: Data can be transmitted over a broadband mobile network or a fixed network. Mass communication network refers to a network used mainly to transmit TV and radio content.

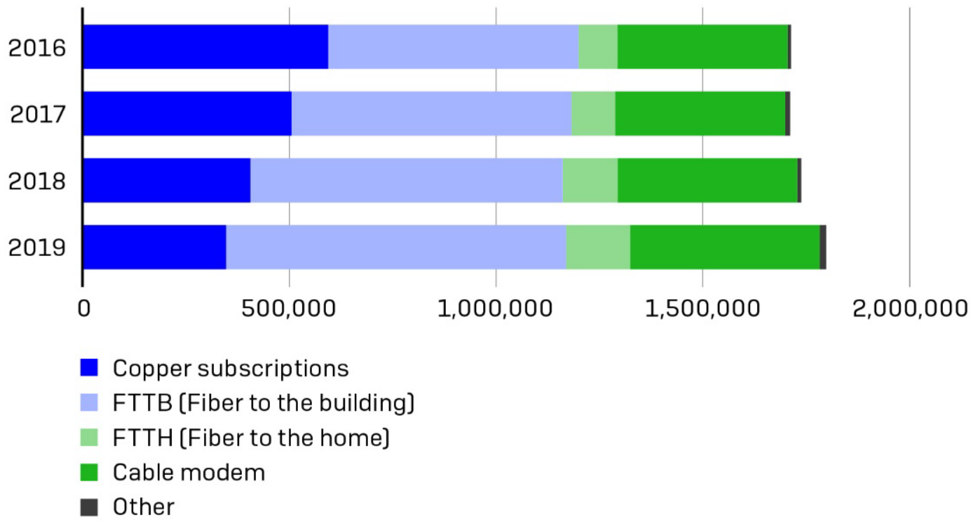


4.1.1 Fixed broadband

Fixed connections are needed above all for services that require high and predictable connection speed. At present, the fastest and most reliable fixed connections are provided using optical fibre and they also serve as the foundation for the high-speed wireless connection transmission network. The deployment of new fibre-optic connections continue to be built and existing copper connections are being replaced with optical fibre.

At year-end 2019, fixed-network broadband subscriptions in Finnish homes numbered around 1.53 million and the number of business subscriptions was around 210,000. While there was only a slight increase in the numbers from previous years, the speeds of fixed-network broadband connections are clearly rising. This is partly due to slower technologies being replaced with newer and faster ones (Figure 10). At year-end 2019, over 40% of all fixed-network broadband connections had a speed in the range of 100–300 Mbit/s, compared to around 35% a year earlier (Figure 11).

Figure 10: The numbers of fixed-network broadband subscriptions have grown slowly. The share of fibre optic connections has increased in subscriptions. Source: Finnish Transport and Communications Agency Traficom.

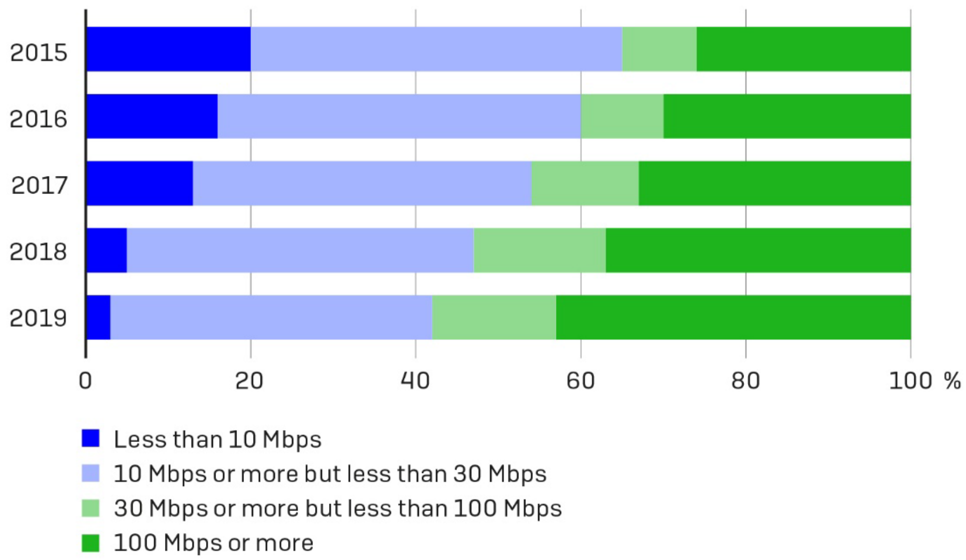


Different connection technologies are available to implement fixed-network broadband:

- Copper connections are broadband connections implemented by means of copper twisted-pair cabling. Broadband digital data transmission in such cases is implemented by using digital subscriber line (DSL) modems between the subscriber and the digital subscriber line access multiplexer (DSLAM). The highest data transmission rate achievable with this technology depends on the type of DSL modem and the length of the subscriber connection. A very high speed digital subscriber line (VDSL2) modem, for example, can achieve a bidirectional net data rate of no more than 200 Mbit/s.[121]

- Fibre to the Building (FTTB) means connections where the fibre-optic cabling reaches at least one building on a given property. In such cases, connection speeds may be restricted by the building's internal cabling, but in most cases such subscriptions permit data transmission at a rate of 100 Mbit/s at least.
- Fibre to the Home (FTTH) are connections where the fibre-optic cabling extends to the apartment. Such subscriptions permit data transmission rates of 1,000 Mbit/s (1 Gbit/s) at least.
- Cable modem subscriptions are implemented by means of the cable television network and can achieve transmission rates of 1,000 Mbit/s.
- Other subscriptions include various wireless solutions implemented with radio technology intended for use mainly in a fixed location. The category also includes all housing company and building subscriptions that do not fall in other categories.

Figure 11: The data transmission rate of fixed-network broadband subscriptions has increased between 2015 and 2019. Source: Finnish Transport and Communications Agency Traficom.



[121] https://www.itu.int/rec/T-REC-G.993.2-201902-I/en

4.1.2 Mobile broadband

As a rule, public mobile communication networks are based on the standards of the European Telecommunications Standards Institute (ETSI) and the International Telecommunication Union (ITU). New generations of devices are denoted by an ordinal number and the letter G for generation. Each new generation in the mobile communication network has introduced new features and services, provided more efficient data transmission and, in respect of certain services, enabled compatibility with earlier generations.

In Finland, telecommunications operators have built extensive 2G, 3G and 4G networks that cover almost the entire country, and the new 5G network is now being built. The Government granted network licences for the 3.5 GHz frequency band in late 2018 and the construction of 5G networks started in early 2019.

Data transmission rates in the mobile communication network depend on a number of factors, but in practice 4G technology allows average rates of no more than 50–100 Mbit/s to be achieved. The maximum transmission rates in the coming next-generation 5G technology may reach several Gbit/s.

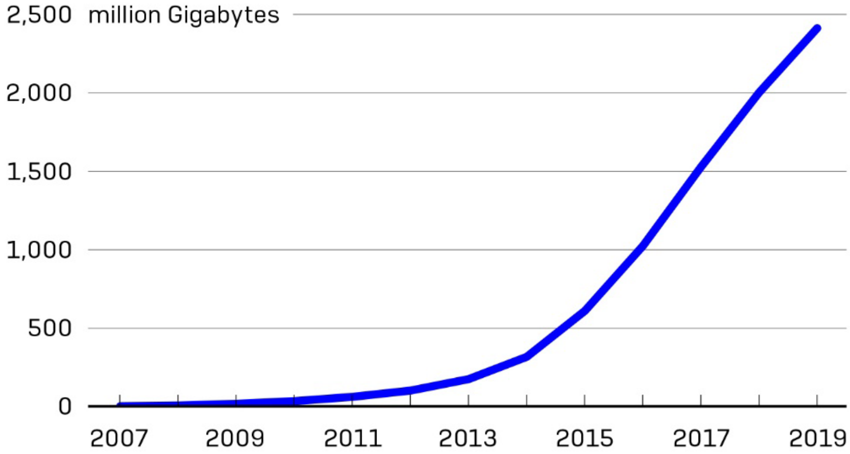
In mobile communication networks, the mobile end user device connection to the radio network base station is accomplished with radio frequencies. The aim in Finland's communication policy has been to allocate as much frequencies as possible to wireless broadband use in order to support Finland's standing as a leading developer and user of mobile networks.

Besides the radio network component, the mobile communication network also always includes fixed network systems used in the mobile network. Regardless of technology employed, mobile broadband always requires a high-speed fibre or radio link connection between the base stations and the core network (Figure 9).

At year-end 2019, mobile broadband subscriptions in Finland numbered well over 2 million. Nearly 80% of these were used by households and almost all included unlimited data (see also chapter 2).[122] The volume of data transmitted over the mobile communication network has rapidly increased in Finland (Figure 12) between 2007 and 2019.

[122] Finnish Transport and Communications Agency Traficom: Statistics on communications services. Updated 18 March 2020. https://www.traficom.fi/fi/tilastot

Figure 12: In 2019, Finland's mobile communication networks transmitted 2.4 million GB of data.



4.2 Network energy consumption and climate aspects

Monitoring the energy consumption and energy efficiency of communication networks over various time periods is difficult due to a lack of consistent data collection practices and statistics. Some isolated statistics and studies are available. In general, the increase in data transmission volumes is regarded as also leading to increases in communication network energy consumption which, however, is at least in part compensated for by improvements in the energy efficiency of the various network devices. In addition to the introduction of new technologies increasing energy efficiency, energy consumption is often also affected by the lifecycle of old devices and device modernisation before the end of their life. The International Energy Agency (IEA) estimates that data networks consumed around 185 TWh of electricity globally in 2015, while data centres worldwide consumed 194 TWh in 2014. This means the share of both would be around 1% of total global electricity consumption. Mobile networks accounted for around two thirds of the global electricity consumption from networks. According to the IEA estimate, the rising popularity of mobile data and the increase in data volume may result, by 2021, in the energy consumption of data transmission networks multiplying, or even decreasing, depending on the impact of policy measures on future energy-efficiency trends.[123] Andrae's updated trajectory for

[123] International Energy Agency 2017: Digitalization & Energy.

the 2020s[124] projects a tripling of the total use of energy for mobile networks (98 TWh -> 316 TWh) and a doubling for fixed networks (150 TWh -> 284 TWh).

According to a study commissioned by the Finnish Federation for Communications and Teleinformatics (FiCom), the total electricity consumption of communication networks in Finland was on the rise during 2014–2018. In 2014, telecommunications operators used around 506 GWh of electricity, while in 2018 the corresponding figure was 634 GWh. Growth in the use the Internet of Things and artificial intelligence and their data intensity were regarded as the determining factors for energy consumption. Transmission of video content over information networks was also found to have increased considerably.[125]

In 2019, the Finnish fixed network consumed an estimated 300 GWh and the mobile network just under 500 GWh of energy. These figures include consumption from lighting, cooling and heating.[126]

4.2.1 Network energy efficiency

There is currently no reliable data available on fixed network data transmission volumes in Finland, which makes it difficult to determine their energy efficiency. Generally speaking, the fixed network is more energy efficient than the mobile network, and international sources[127] report energy intensities of 0.0043 kWh/GB in connections between subscriber and operator and 0.052 kWh/GB in core networks.

According to the above-mentioned FiCom study, the specific electricity consumption, or energy efficiency, of mobile data was around 1.6 kWh/GB in 2014 and had improved to 0.3 kWh/GB in 2018.[128] A preliminary study on the electricity consumption and energy efficiency of base stations of mobile networks commissioned in 2015 by the Finnish Communications Regulatory Authority (FICORA) from VTT Technical Research Centre of Finland projected an increase in energy efficiency per gigabyte as traffic loads grow and capacity utilisation rate improves. According to the study, operators were also able to increase the efficiency of their direct consumption of

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[124] Andrae 2020: Hypotheses for primary energy use, electricity use and CO_2 emissions of global computing and its shares of total between 2020 and 2030. WSEAS Transactions on Power Systems.
[125] https://www.ficom.fi/ajankohtaista/uutiset/digitalisaatio-auttaa-energiatehokkuudessa-–-ja-tarvitsee-siihen-sähköä
[126] Data collected by the Finnish Transport and Communications Agency Traficom from the largest telecommunications companies, spring 2020.
[127] Schien et al. 2015: The Energy Intensity of the Internet: Edge and Core Networks. ICT Innovations for Sustainability.
[128] https://www.ficom.fi/ajankohtaista/uutiset/digitalisaatio-auttaa-energiatehokkuudessa-–-ja-tarvitsee-siihen-sähköä.

electrical energy through voluntary measures during 2011–2014 despite the very high increase in the volume of data transmission over the same period.

The energy consumption of communication network devices is a significant cost factor for telecommunications companies and device manufacturers. The power needed affects the requirements set for the network, such as the dimensioning of backup power capacity and equipment facilities and their cooling. Consequently, energy consumption can be assumed to be a main driver in the context of equipment procurement and network design. On the other hand, a priority in efforts to improve energy efficiency has been not to slow down broadband development or jeopardise the achievement of service level objectives.[129]

There is fairly little compiled new data available on the energy consumption and energy efficiency of the various communication network systems, devices and components that would enable unequivocal assessments or comparisons of energy consumption between network devices. The assessment of the network itself and its various components in relation to total end-to-end energy consumption of a given service is also challenging with regard to services connected to the internet. This is because service provision requires not only public communication networks but also private networks of businesses and organisations as well as combinations of these.

The distinction between network and data centre is blurring to some extent, as some of the computation for new network technologies and services is shifting from centralised data centres towards the edge of the network. In addition to this, in many cases the delivery of a specific service in the provider's infrastructure involves not only the actual servers but also a significant amount of network devices regarded as components, such as routers and switches. This also means that it is no longer possible to draw a clear line between the energy consumption of networks and data centres.

Moreover, network technology is evolving very rapidly, with various network components and even architecture being replaced in response to requirements such as network capacity, service capacity and application needs of users. Therefore the characteristics of networks and their components may vary a great deal as regards energy efficiency, too.

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[129] Finnish Communications Regulatory Authority (FICORA), 2012: Laajakaistaisten viestintäverkkojen energiatehokkuus. Viestintäviraston siirtojärjestelmät-työryhmän muistio. [Energy efficiency of broadband communication networks. Memorandum of FICORA working group on transmission systems.]

Factors relating to energy efficiency concerning a few networks are examined below.

Fixed broadband networks

At the request of the Ministry of Transport and Communications, the FICORA working group on transmission systems examined in 2011 and 2012 the energy consumption of communication networks and the energy efficiency (W/Mbit/s) of the various transmission technologies.[130] According to the working group's report, the user-specific power consumption in copper/DSL technology access networks at 10 Mbit/s upload and download speeds appeared to be below 10 W per user. This figure was arrived at in the light of the target values employed at the time. When applying more recent target values based on the EU Code of Conduct from 2017, power consumption would have roughly halved from this. However, with DSL technology, power consumption – and consequently also energy efficiency –depends greatly on the length of the subscriber line and the data transmission rate, so in practice power consumption may also be higher.

The report also stated that the ratio often used in fixed broadband energy comparisons is 1:10, i.e. a digital subscriber line access multiplexer (DSLAM) consumes around one tenth of the energy required by the home end user devices and modems connected to it. It was also found that the energy consumption of home end user devices (computers, televisions) already with 2–3 hours of daily use is considerably higher than the energy consumption of data communications equipment (DCE).

The per-user energy consumption of devices required in fixed subscriber network connections based on other technologies (optical network, cable TV network) would not appear to differ significantly from DSL technology at 10 Mbit/s. This is also supported by a study from 2011 comparing per-user power consumption of different technologies and speeds.[131] The study found that e.g. the per-user power consumption in hybrid-fibre coaxial (HFC) networks is around 8 W per user but rises rapidly when connection speed exceeds 20 Mbit/s. DSL system power consumption was found usually to be lower than that of optical systems, but with DSL the range would be limited to around 20 Mbit/s. Fixed optical access networks were found to be

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[130] Finnish Communications Regulatory Authority (FICORA), 2012: Laajakaistaisten viestintäverkkojen energiatehokkuus. Viestintäviraston siirtojärjestelmät-työryhmän muistio. [Energy efficiency of broadband communication networks. Memorandum of FICORA working group on transmission systems.]
[131] Baliga et al., 2011: Energy Consumption in Wired and Wireless Access Networks. IEEE Communications Magazine.

clearly more energy efficient than other transmission technologies, especially at high connection speeds.

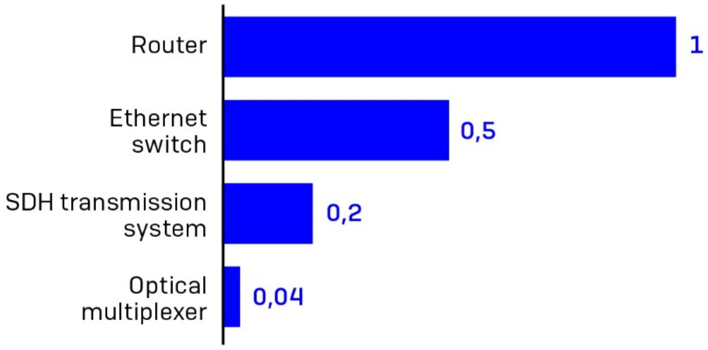
In practice, subscriber end devices are rarely in constant use. While not in on mode, devices are put into idle mode that consumes less power and therefore reduces energy consumption to some extent.

In addition to systems intended for actual data transmission, area networks and core networks also use switches and routers to direct data frames or packets to their intended destinations. As the names imply, switch switches data packets transferred usually between physical ports of devices within a network administered by the same organisation while a router routes data packets transferred also between networks administered by different organisations. In practice, the same device may have both switch and router functionality (Layer 2/3) or perform routing only (Layer 3).

According to a study, the share of Layer 2/3 devices has grown continuously in large enterprise networks.[132] This development can also be seen in area and core networks of public networks.[133] Comparisons of their power consumption have yielded the percentages shown in Figure 13.[134] It was concluded that, from the power consumption perspective, efforts should be made to avoid signal processing at the higher protocol layers used for data transmission control. On the basis of these studies, optical data transmission appears to be the most energy efficient network technology.

[132] https://greenelectronicscouncil.org/wp-content/uploads/2019/04/20190401_GEC_TÜV_LNE_Final_Clean.pdf
[133] Finnish Communications Regulatory Authority (FICORA), 2012: Laajakaistaisten viestintäverkkojen energiatehokkuus. Viestintäviraston siirtojärjestelmät-työryhmän muistio. [Energy efficiency of broadband communication networks. Memorandum of FICORA working group on transmission systems.]
[134] Di Giglio et al., 2011: Green features of STRONGEST. Vision, rationale and status. STRONGEST workshop, Pisa.

Figure 13: The power consumption of network devices is higher at the higher layers used for data transmission control.



Broadband mobile networks

More than 80% of mobile network energy consumption typically occurs in radio network parts and, overall, the share of the radio network in total mobile network consumption has increased in recent years.

The world's first 2G GSM network was launched in Finland in 1991. Since then, the energy efficiency of networks has increased considerably with each new generation of technology. Compared with 3G technology, 4G is around ten times more energy efficient. The 5G standardisation process of the International Telecommunication Union (ITU) seeks to increase network energy efficiency (Joules per bit) by a factor of 100 compared with 4G technology. According to Recommendation ITU-R M. 2083-0 (2015), the switch to 5G should not result in greater energy consumption in the radio network regardless of the increased network capacity. This has even been estimated to enable a historical decoupling of GDP growth and carbon dioxide emissions. However, the denser base station network required by 5G compared with 4G technology presents its own challenges regarding total energy consumption.

5G technology is standardised by the 3rd Generation Partnership Project (3GPP), the umbrella organisation for telecommunications standard development organisations. The first version of a 5G standard, Release 15, was completed in 2019, and Release 16 is due for completion in the second half of 2020. Technology development work will continue after that, too, with new technical functionalities added continuously to the standard. 5G standards contain many new features such as ones that increase connection speeds, reduce latency and enable a very large number of devices connected to the network as well as features designed to lower the energy consumption of end user devices. As a rule, the features developed for earlier 2G, 3G and 4G networks can continue to be used in new 5G networks as well.

Evolving and extremely high-performing networks enable greater data speeds and increases in the volume of data transmitted, which poses a challenge as regards improving energy efficiency. With old technologies remaining in use alongside new ones, the benefits of increases in energy efficiency cannot be leveraged to the fullest extent, either. Congestion also increases the amount of energy consumed by networks.

Terrestrial television networks

TV distribution network access technologies, i.e. devices and technologies used by consumers, account for a significant percentage of the total energy consumption of the service (up to 70%[135]). Access technologies for multichannel TV distribution are as follows:

- watching terrestrial and cable TV broadcasts on television
- watching video-on-demand on internet-connected television
- watching video-on-demand on a computer
- watching video-on-demand on a handheld device (phone, tablet).

In Finland, the network operator for terrestrial television networks in the UHF band is Digita. In recent years, the average electricity consumption of these networks has been 27,000 MWh, while the volume of data (video, sound) transmitted in 2019 totalled 34 million GB. The terrestrial TV distribution network transmits 22–160 Mbit/s to homes around the clock.

The terrestrial TV distribution network has accounted for an estimated 48–50% of the reception of the total number of TV households in recent years. Altogether 1.216 million households use terrestrial television as their primary source of TV[136], and these households have an average of 1.7 televisions. When estimating that a television consumes 150 W of electricity and knowing that the average daily TV viewing time is 2 hours and 42 minutes, total consumption comes to 173,000 MWh. Based on this data, the terrestrial television distribution network would, in multichannel TV distribution, account for around 15% of the total electricity consumption of access technology and core and transport networks. It should be noted that devices used for terrestrial TV reception can be used for reception from other distribution platforms, too.

[135] https://www.vttresearch.com/sites/default/files/julkaisut/muut/2015/VTT-CR-01429-15.pdf
[136] https://www.finnpanel.fi https://www.finnpanel.fi/en/tulokset/tv/vuosi/sharev/viimeisin/ https://www.finnpanel.fi/lataukset/tv_year_2020.pdf

The most substantial difference between the terrestrial TV distribution network and general-purpose data networks in terms of energy efficiency is related to their different topologies and manners of use. TV distribution networks have been designed for use in “fixed” reception (with a fixed rooftop aerial) and with a unidirectional broadcast path based on the needs of linear media distribution. The network as a whole is highly energy efficient given its transmission capacity and user potential.

As is the case with other distribution networks, too, the energy efficiency of mass communication networks and especially the terrestrial TV distribution network has increased significantly in Finland thanks to network investments and upgrades of device and system technology made over the past decade. In TV distribution networks, energy efficiency is increased by:[137,138,139]

- a technology shift from DVB-T to DVB-T2 technology, which reduces the energy consumed in the transmission network per volume of data transmitted due to improved capacity;
- development of image and video coding methods (such as H.264 and H.265), which enables better image quality with lower data rates;
- a transmission network technology shift (from SDH technology to IP-based data transmission), which together with evolving coding methods enables the optimisation of data transmission capacity according to data transmission needs. Changeover in IP-based data transmission solutions from unicast to multicast on the part of data network operators also enables increases in energy efficiency per volume of data transmitted;
- improved efficiency of power supply and amplifier stage components in broadcasting platforms, which enables reductions in the energy consumed for TV broadcast signal per volume of data transmitted;
- efficient use of frequencies in the terrestrial TV distribution network, utilising high-power broadcasting and a nationwide network of tall-mast transmitting stations and extensive single frequency network (SFN) solutions.

Energy consumption is specific to each transmitting station due to TV transmission network parameters, network coverage areas, radio licensing and government regulations as well as customer agreements. The importance of the terrestrial TV distribution network in emergency conditions requires special distribution network backup measures at the level of network as well as transmitting station, which affects energy efficiency.

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[137] https://www.vttresearch.com/sites/default/files/julkaisut/muut/2015/VTT-CR-01429-15.pdf
[138] https://www.gatesair.com/documents/news/Transmitter-Systems-Efficiency-and-TCO-BBR4-GA.pdf
[139] https://www.rohde-schwarz.com/lt/product/thu9evo-productstartpage_63493-313345.html

Analogue radio networks

An analogue radio distribution network is a mass communication network that functions efficiently in the distribution of audio content across a broad geographic area. There are currently 968 analogue radio transmitters in use in nationwide, regional and local radio networks in Finland. The number of transmitters in use has increased by around 4% per year since 2012. Going forward, growth will be limited by the amount of available frequencies. Alongside terrestrial television networks, the energy efficiency of radio networks has also improved thanks to investments as well as equipment and system upgrades. Over the longer term, radio distribution is likely to move increasingly into broadband networks due to changes in media consumption.

4.2.2 Standardisation and international cooperation

Issues related to the climate and environmental impacts of communication networks, such as energy efficiency and device lifecycle management, have long been addressed in international standardisation, too. The topic has been examined quite extensively by organisations such as the International Telecommunication Union (ITU) and the EU.[140,141,142] The European Commission's 2019 Rolling Plan for ICT Standardisation[143] also contains a section on the environmental impacts of ICT as well as related policy and legislation objectives, proposed actions and standardisation activities. A key challenge identified in the policy objectives is achieving transparency around claims relating to the environmental performance of ICT products and services, and setting an effective basis to drive competition.

One of the requested actions in the Commission's Rolling Plan is the definition of global key performance indicators (KPIs) for the energy management of fixed and mobile access and core networks. It is stated that many standardisation organisations have roles and activities for the definition of energy-efficient KPIs and their measurement and monitoring. European Telecommunications Standards Institute (ETSI) standards in particular are regarded to have good coverage of the design of various network types and components from the energy-efficiency perspective and to provide tools to monitor the energy management of networks.

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140 ITU-T, 2012: Recommendation Y.3021 Framework of energy saving for future networks. https://www.itu.int/rec/T-REC-Y.3021-201201-I/en

141 European Commission, 2017: EU Code of Conduct on Energy Consumption of Broadband Equipment. https://publications.jrc.ec.europa.eu/repository/bitstream/JRC106039/ictcoc-ecbe-v6_feb_2017_final.pdf

142 ITU-R, 2015: Recommendation M.2083-0 (09/2015) IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond.

143 European Commission, 2019: Rolling Plan for ICT Standardisation.

In spring 2020, the Radio Spectrum Policy Group (RSPG), a high-level advisory group assisting the European Commission, appointed a new working group to identify climate change-related aspects within spectrum management. Another question to be addressed is how spectrum management can help combat climate change. The reports will be used to produce EU-level recommendations. The Body of European Regulators for Electronic Communications (BEREC) has also created a new Expert Networking Group on Sustainability. Finland is represented in these groups by the Finnish Transport and Communications Agency Traficom.

4.3 Network use, production and end-of-life treatment, recycling

4.3.1 Lifecycle management in general

The biggest environmental impacts of networks arise from their in-use energy consumption. For example, around 93% of the calculated lifetime carbon dioxide emissions of mobile networks come from their use, 7% from manufacture including components and materials and 1% from logistics. The percentage of in-use emissions has increased gradually in recent years.[144] In-use greenhouse gas emissions depend on the amount of electricity consumed and the emission factor of the electricity consumed (see subsections 2.2.3 and 4.3.2).

The big picture of climate and environmental impacts of ICT networks as well as other ICT goods and services should be examined from the perspective of their entire lifecycle starting from design and ending with dismantling or disassembly and recycling. International standards and recommendations, such as the International Telecommunication Union Recommendation ITU-T L.1410, provide highly detailed guidelines and definitions for the management of the climate and environmental impacts of ICT network components and for impact reporting.

Greenhouse gas emissions reporting should disclose data on the share of emissions from raw material acquisition, production, use and end-of-life treatment. In practice, reporting at such a comprehensive level is not available.

[144] https://www.nokia.com/sites/default/files/2020-03/Nokia_People_and_Planet_Report_2019.pdf

4.3.2 Energy consumption and carbon footprint reporting of telecommunications companies

According to their environmental responsibility disclosures, all three of the biggest telecommunications companies operating in Finland – DNA, Elisa and Telia – report their lifecycle emissions at least in general terms. The reports do not enable comparable conclusions concerning the companies or any specific assessments of the roles of networks and their lifecycle stages as generators of greenhouse gas emissions. The environmental reports of these companies do, however, to some extent disclose data in compliance with calculation principles of the Greenhouse Gas (GHG) Protocol[145], whereby GHG emission data can be disclosed in accordance with the following classification:

- Scope 1: The company's direct (own) GHG emissions
- Scope 2: Emissions from the purchased electricity consumed by the company
- Scope 3: Other indirect GHG emissions.

The DNA Corporate Responsibility Report states that the company's climate-friendly operations objective is to reduce energy indirect greenhouse gas emissions (Scope 2) by 100% by 2023 from the level reported in 2014. In addition, DNA will adjust the emission calculation methods for its main product categories and set a Scope 3 climate objective accordingly.

In 2019, DNA's energy indirect greenhouse gas emissions (Scope 2) were 13,400 tonnes, down 25% from 2018. Since 2014, DNA's Scope 2 emissions have decreased by approximately 55%, which is due to procurement of renewable energy and increased energy efficiency in the radio networks. In 2019, the method for collecting source data relating to the procurement of purchased electricity (Scope 2) was adjusted to improve comparability. The Scope 2 emissions reported are based on both measurement and estimation. DNA reports that its directly procured energy is hydro or wind power and comes with a Guarantee of Origin.

Elisa states that its objectives include reducing its carbon footprint from energy consumption by 50% by 2025 compared to 2016.[146] Elisa reports a carbon footprint of 4,806 tCO_2 for 2019. According to Elisa, the company's Scope 1 and 2 carbon footprint has decreased by around 63% since 2016. The company has joined Energy

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[145] https://www.wri.org/publication/greenhouse-gas-protocol
[146] https://corporate.elisa.com/attachment/elisa-oyj/annual-report-2019/Elisa_Responsibility_Report_2019.pdf

Efficiency Agreements concluded as part of Finland's National Energy and Climate Strategy.

According to Elisa, the company has reduced its electricity consumption per data bit by approximately 65% since 2015 thanks to new technology and the optimisation of its mobile networks. The energy efficiency of mobile data transmission reported by Elisa for 2019 is 0.2 kWh/GB, when in 2016 it was 0.6 kWh/GB.

Telia states in its Environmental Report[147] that its carbon footprint covering the entire value chain was approximately 250,000 tCO_2e in 2019. Of this, the share of Telia's own emission sources (Scope 1) in accordance with the Greenhouse Gas (GHG) Protocol was 0.4%, while emissions from purchased energy (Scope 2) made up around 1% of the total. The majority, more than 98%, of Telia's emissions are other indirect emissions (Scope 3), which are generated through purchased products and services and emissions generated by the use of products and services sold. The in-use emissions of products and services sold account for around one fifth of the total emissions of Telia's value chains. Around one tenth of Telia's emissions are emissions generated in the production phase of industrial goods, mainly network equipment.

Telia has joined an Energy Efficiency Agreement for 2017–2025 and is committed to improving its energy efficiency by 7.5% by 2025 from the baseline in 2015. In 2019, it achieved energy savings of 6.6%.

The companies' environmental disclosures do not itemise the percentage of communication network energy consumption or emissions of the total. Their reports focus on examining the development of energy efficiency and calculated emissions, with less data provided on energy consumption.

4.3.3 Recycling of equipment and materials

Waste such as waste electrical and electronic equipment (WEEE) or removed asphalt is generated from network construction, maintenance and updating. The amount of waste generated can be reduced by reusing equipment and recycling materials. Companies most commonly deliver waste to specialised waste treatment operators that take care of its appropriate treatment, including directing fractions suitable for recycling to material recovery. Equipment manufacturers can facilitate the reuse of

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[147] https://www.telia.fi/dam/jcr:098dac6e-2c08-4a4c-9deb-641371775aed/Environmental_report_Telia_2019.pdf

devices and materials by taking back used devices and forwarding them for material recovery and recycling.

According to a survey conducted in 2020, around three quarters of the active and passive network components of the fixed network are recycled in Finland. This includes all cabling and related elements, such as protective pipes. Telecommunications companies are estimated to recycle more than half of the mobile network base station components and infrastructure constructed for base stations, but their estimates of the volumes recycled vary significantly.[148]

There is also variation in the estimates provided by telecommunications companies about the service life of network components and equipment. The service life of active elements in the mobile network is currently estimated to average 7–10 years and that of passive network elements 10–20 years. The development of active mobile network elements towards cloud-based elements shortens their service life. In the fixed network, the service life of copper network components is estimated to average 10–25 years and that of optical fibre network components 10–20 years.[149]

The updatability of software is essential due to the rapid development of technologies. Circular economy thinking can be utilised in the following ways in mobile networks:

- equipment design: choice of components and materials, labelling, design for disassembly
- extending equipment life: no-touch updates of software
- equipment maintainability: 24/7 maintenance services provided by manufacturers
- reuse of equipment, modules and components and warranty repairs for reuse (e.g. 56,300 Nokia product units were reused in 2019)

responsible recycling of materials (e.g. Nokia recycled 4,000 tonnes in 2019, of which 91.6% comprised material recovery and 7.7% energy recovery).

4.4 Role of future network technologies

Research into 6G is already ongoing alongside the rollouts of 5G networks. Appointed by the Academy of Finland in May 2018 and headed by the University of Oulu, the 6G

[148] Data collected by the Finnish Transport and Communications Agency Traficom from the largest telecommunications companies, spring 2020.
[149] Data collected by the Finnish Transport and Communications Agency Traficom from the largest telecommunications companies, spring 2020.

Flagship[150] programme has taken on the role of beacon in international 6G research, which represents an opportunity for all of Finland's long-term ICT sector development. The vision for 2030 of the 6G Flagship programme[151] reads, "Our society is data-driven, enabled by near-instant, unlimited wireless connectivity."

The wider deployment of 6G is estimated to take place in the early 2030s.

4.4.1 6G network architecture

The current network architecture is constantly evolving and will continue to be used in the future as well, but it is being joined by 6G network solutions that are different in architecture. The 6G network of the future[152] is a service platform that, besides data transmission, utilises numerous other services to allow e.g. virtual world content to be integrated with the physical world. 6G networks will make it possible to integrate the data transmission service with services such as computing, positioning, 3D modelling, imaging and other sensor-based services linked to access to local contextual data. This will pave the way for the development of entirely new kinds of services.

The virtualisation development that started with 5G networks will continue in 6G and enable the extensive utilisation of general-purpose computing equipment to implement various functionalities in the different parts of the network. The change in network architecture in 6G will lead to increasing structural complexity where the locations and volumes of data collection, storage and processing can be optimised among end user devices, local edge clouds and centralised cloud solutions.

Computing volumes are going to increase significantly. On the other hand, the change in architecture will help optimise computing location on the basis of e.g. latency and capacity requirements and also to avoid unnecessary transmission of data. Networks will grow more intelligent, which will enable proactive instead of reactive operations. The overall impacts on climate and the environment of this complex and distributed whole are as yet difficult to assess.

6G development is divided on the one hand between very fast short-range networks that leverage new, ultra-high frequency bands in the THz spectrum and on the other, large-coverage solutions especially in areas where connectivity is deficient at present. The dependence of cell size on the available radio frequency bands will lead to

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[150] www.6gflagship.com
[151] 6Genesis vision for 2030https://www.youtube.com/watch?v=T6ubRoZCeVw
[152] Latva-aho & Leppänen 2019: Key Drivers and Research Challenges for 6G Ubiquitous Wireless Intelligence. 6G Flagship White Paper. University of Oulu.

smaller cell sizes when moving into the higher frequencies, which will have an impact on the construction and energy consumption of networks.

The deployment of 6G technology calls for new kinds of internal network solutions because, as things now stand, outdoor base stations alone will not be able to provide sufficient performance. In addition to new kinds of indoor coverage solutions, the implementation of internal networks will likely necessitate fibre-optic connections to be run right up to buildings. The wide-ranging utilisation of fibre-optic connections is therefore perceived as central to network solutions of the future where wirelessness is a part of the network architecture. The rise in the significance of internal networks will also serve to localise loads, which in turn will require optimisation to minimise ICT loads.

Emphasis on the local nature of networks is characteristic also of 5G networks, the deployment of which has internationally resulted in the emergence of local 5G networks to complement the nationwide networks of mobile communications operators.

4.4.2 Role of sustainable development in 6G

The social, economic and environmental Sustainable Development Goals (SDGs) of the UN 2030 Agenda for Sustainable Development have come to occupy a central position in the ICT sector development pursued worldwide as well as in 6G research.[153] The role of 6G is proposed to be seen to consist of three distinct viewpoints: 1) as a provider of services to help steer communities and countries towards reaching the SDGs, 2) to enable measuring tools for data collection to help reporting of indicators with hyperlocal granularity, and 3) as a reinforcer of a new 6G ecosystem to be developed in line with the SDGs.

The development of 6G systems can also be seen to require new indicators compared to the sets of minimum technical requirements for earlier generations of the International Mobile Telecommunications (IMT) systems defined by the ITU. The need is for indicators that better cater for the promotion of the SDGs instead of e.g. just comparing volumes of data transmitted. Improving energy efficiency and obtaining real energy consumption data from the various parts of the network and end-to-end with different configurations become central aspects of responding to the challenge of increased loading. In this respect, the importance of research is underscored.

[153] Matinmikko et al. 2020: White Paper on 6G Drivers and the UN SDGs. Draft. https://www.6gchannel.com/wp-content/uploads/2020/04/6g-white-paper-6g-drivers-un-sdgs.pdf

Leveraging ICT in other sectors to advance the SDGs would require these fields to be closely involved already at the system design phase.

Finland has numerous ICT companies but a small domestic market for ICT. ICT solutions in support of sustainable development, geared to the export market, represent an opportunity for Finland. Self-sustainable 6G base stations are one example of the innovation of new solutions.

4.5 Tools to manage climate and environmental impacts of networks

Climate and environmental impacts of networks could be curbed by tools such as technological solutions to increase the energy efficiency of network technologies, renewable electricity solutions, and various solutions relating to construction.

4.5.1 Tools to improve mobile network energy efficiency

The following tools could be deployed to reduce the in-use electricity consumption of mobile networks:

- Age of base station generation: Modernisation of 2G, 3G and 4G reduces energy consumption by an average of 46%.[154]
- 2G, 3G, 4G and 5G radio technology used: The later radio generations are more efficient than the older ones. 5G standardisation aims to accomplish energy efficiency (Joules per bit) of up to 100 times greater than 4G[155]. The energy efficiency of 4G is estimated to be 10 times greater than that of 3G.
- Density of the base station network: the lower the radio frequency used, the less energy is required per km^2 (radio coverage) and the more frequencies are in use, the less energy is required per Gbit/s (radio capacity)[156]. However, connection speeds equal to those of higher frequency bands cannot be provided with lower frequency bands owing to the narrowness of the bands. The more different frequencies become available, the more base station equipment is needed, unless the base station is capable of supporting multiple frequency bands.

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[154] Nokia.
[155] ITU-R M. 2083-0 (2015).
[156] Nokia.

- Activation of energy-saving features outside peak hours: putting resources into sleep mode delivers average savings of 10–30% of the energy required by the base station. Besides device-specific energy-saving features, also smart algorithms based on the network's traffic profile can be used.
- Base station equipment facility cooling devices: air cooling equipment typically consumes 30–60% of the equipment facility's total energy, and liquid cooling can deliver savings of more than 90% in cooling energy. When the waste heat recovered by liquid cooling is used in the vicinity of the equipment facilities, the total emissions of the base station can be reduced by up to 80%.
- Base station facilities also contain other energy-consuming equipment such as power feed systems, stand-by systems and facilities lighting and alarm systems, which can be optimised and modernised to reduce energy consumption.

Major energy consumption-reducing features of 5G networks:

- 5G Lean Carrier. 4G networks use very dense signalling, which increases energy consumption. The signalling volume is much lower in 5G networks. This feature reduces energy consumption by an average of 55% and up to 80% at best.
- Using traditional radio (2x2 MIMO, 4x4 MIMO), 5G software consumes 55% less energy on average than 4G software.
- While 5G Massive MIMO or mMIMO (e.g. 64x64 MIMO) radio consumes on average three times more energy than traditional radio, mMIMO increases radio capacity roughly five-fold, which enables 55% lower energy consumption, on average, compared to traditional MIMO radio. mMIMO radio is typically used when running out of frequencies so as to prevent the densification of the base station network.
- The new high 5G cm and mm-wave bands are many times wider than the existing 4G frequency bands – 100 MHz wide 5G band, for example, is five times wider than e.g. 20 MHz LTE band – which allows around 5.5 times more traffic on the same radio. The additional capacity from new frequencies will reduce the need to make the current network of base stations denser.
- In sparsely populated areas, it is important to efficiently use frequency bands of under 1 GHz to enable maximal coverage with as sparse a base station network as possible. At the same time, low frequencies will enable better indoor coverage inside buildings also in densely populated areas.

4.5.2 Renewable energy production at base station sites

In addition to using electricity from renewable sources (see subsection 4.3.2.), the carbon intensity of network electricity consumption can be influenced on a small scale by producing renewable energy at base station sites. Globally around 1% of base station sites have renewable energy production. In Finland, solar power is not attractive as the only source of energy due to the reasonable price of electricity and the excellent quality of the power transmission grid. Instead, solar power is an excellent option for providing some of the energy required by base stations when expensive storage is not applied.

Cost accounting for solar power differs from base station costs, as the life of solar panels – typically exceeding 30 years – is many times longer than that of base stations. Over the past ten years, solar panel prices have fallen by more than 90%, and most base station sites have space for at least one panel. A small solar installation providing energy 11% of the time (1,000 hours a year) can cost as little as EUR 1,000.

Rationale for greater use of solar power at base stations could also be found in power distribution network balancing. In recent years, power grid reliability in sparsely populated areas in particular has declined, especially due to reactive power from heat pumps, and this may cause problems in the use of low-power LED lights in particular. When controlled correctly, a backup battery system set up in conjunction with solar power can act as a factor stabilising the power grid. VTT Technical Research Institute of Finland is conducting research into powering the 5G test network with solar electricity in the Finnish city of Oulu. The aim is to find an arrangement through which the system will provide the widest possible benefits for the 5G test network and the electricity distribution network alike.

4.5.3 Network sharing and joint construction

Network sharing means that telecommunications companies providing network services use the same physical network for their service provision. Sharing does not reduce the in-use electricity consumption of base stations, but it does reduce the total number of base station sites as it eliminates the need to build overlapping networks. This way, it reduces the need to build passive components in particular, such as masts and other base station sites, and lessens related environmental impacts. For example, in eastern and northern Finland a shared network is used by DNA and Telia Finland under their joint venture, Finnish Shared Network Ltd.

Some of the measures included in Finland's Digital Infrastructure Strategy[157] may be regarded as having positive environmental impacts. Construction of passive infrastructure, particularly in connection with underground electricity cabling, as well as the joint construction of networks will not only bring down construction costs but also reduce adverse environmental impacts by trimming down the use of construction-related work phases and materials and also by cutting waste and emissions from construction. The sharing of passive infrastructure in turn can increase the efficiency of electricity use relating to e.g. shared IT areas.

Passive infrastructure means all such physical structures that can be used for building communication networks, i.e. various types of pre-installed underground conduits, manholes, equipment facilities, towers, masts and poles.

Joint construction in turn means that the excavation required for the different utility networks – such as electricity, telecommunication, transport and water supply – is performed jointly. Infrastructure for multiple networks is constructed at the same time, and the costs are shared by the participants. The Finnish Joint Construction Act (276/2016) entered into force on 1 July 2016 and lays down provisions on both the sharing of existing networks and the joint construction of new infrastructure. The Act obliges network operators to allow another network operator to use their physical infrastructure as well as to agree to another network operator's request for joint construction on fair and reasonable terms. An operator may only refuse the use of infrastructure and joint construction on grounds specified in the Act.

4.5.4 Other tools and environmental aspects of networks

In construction supporting sustainable development, new telecommunication needs and related technical solutions should also be taken into account early enough as regards real property and closely related other infrastructure alike. This means cooperation between the various parties in land use planning, design and implementation of construction.

Fibre-optic networks should be constructed in areas where this is economically viable from the viewpoints of energy efficiency and future capacity needs. At the very least, in the context of other passive infrastructure construction, provision should be made for the later implementation of the fibre-optic network in a manner minimising the environmental impacts of construction. Maximising the use of existing structures can

[157] Ministry of Transport and Communications 2018: Turning Finland into the world leader in communications networks – Digital Infrastructure Strategy 2025.

help minimise construction-related use of materials. In addition, methods such as micro-trenching help reduce materials consumption and offer an environmentally friendly approach to fibre-optic network construction.

Airtight and energy-efficient buildings have been found to increasingly interfere with radio signals, which has been estimated to result in reception problems inside buildings. In this context, the Ministry of Transport and Communications published in 2013 the report of a working group on mobile network reception problems in low energy buildings.[158] The short-term measures recommended by the working group were to determine a radio signal strength indicator for the most common building materials, to provide for intrabuilding mobile network cabling, and to develop home base station solutions. The working group’s longer-term recommendations include the promotion of legal mobile repeaters, an increased research effort into possible solutions, and increased openness and cooperation in drafting legislation in the environment and communications sector.

Aspects taken into account in new construction as well as in the renovation of existing buildings should include ensuring that the internal networks constructed also meet future service needs and will therefore be usable for decades to come. Finnish Transport and Communications Agency Traficom Regulation 65 has been issued for this purpose.[159] The regulation applies to the internal communication networks and systems of residential properties intended for permanent residence as well as of commercial and public properties. Solutions relating to internal networks, their construction, upgrade and renovation have far-reaching effects. As the designed lifetime of internal networks is at least 20 years, it is important to also systematically consider future needs in decision-making, procurement and work relating to internal networks. The regulation is premised on making it possible in every residential, commercial and public property to subscribe to fast fixed internet access, i.e. broadband services (e.g. the generic cabling system referred to in the Regulation enables a minimum speed of 1 Gbit/s in the internal network) and to receive ordinary television transmissions from a terrestrial or cable television network.

[158] Ministry of Transport and Communications 2013: Mobile network reception problems in low energy buildings. Working group report.
[159] Finnish Transport and Communications Agency Traficom: Regulation 65 D/2019 on internal networks and telecommunications contracting in properties.

Taking future telecommunication needs into account within properties will also be important as IT areas relating to telecommunications will be required increasingly to implement more and more diverse ICT services for businesses and homes alike. For property and housing companies as well as individual one-dwelling houses, this may mean setting up new types of equipment facilities for wired and wireless network subscriber devices.

5 End user devices

The digital transformation of industry and new digital services enable new forms of manufacturing, work and leisure that are also friendlier to climate and the environment. This also entails a rise in the volume of electronics, however. The global consumption of materials is projected to more than double between 2015 and 2050.[160] Electronics waste is currently the fastest-growing waste stream in the world, with an annual increase of up to 6.5%.[161]

The rising performance of end user devices and their new features have caused older devices to be discarded at a growing pace. A fair number of the devices discarded would still be serviceable.[162] The world over, 20–35% of electronics waste is efficiently collected and recycled.[163,164,165] Only a small portion of the valuable rare earth elements contained in this waste can currently be economically viably recovered.

The sections below will examine the share of consumer devices, tabletop computers, laptop computers and tablets, smartphones and smartwatches, and smart televisions in the ICT service chain. Network equipment and IT equipment in data centres are briefly examined in chapters 3 and 4 above. However, their detailed examination, like that of industrial process equipment, has been excluded from the scope of this report. IoT devices are examined in chapter 7 on emerging technologies.

5.1 End user device demand

Based on data collected in the UK, more than half buy a new smartphone every two years while one in five buys one at intervals of 3–5 years. Just under 10% buy a new smartphone every year. A new tablet is acquired less frequently, mostly at intervals of 3–5 years, while computers are traded in at the same rate or less frequently.[166] Even if newer models were more energy efficient than their predecessors, it has been estimated that a smartphone, for example, would have to be used for at least 25 years

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160 European Commission 2019: European Union Reflection Paper - Towards a Sustainable Europe by 2030.
161 Sullivan 2018: Printed Electronics: Global Markets to 2022. BCC Research LLC.
162 IIASA 2019: TWI2050 - The World in 2050. The Digital Revolution and Sustainable Development: Opportunities and Challenges.
163 World Economy Forum 2019: A New Circular Vision for Electronics.
164 Ellen MacArthur Foundation 2017: Circular consumer electronics: an initial exploration.
165 https://circulareconomy.europa.eu/platform/en/news-and-events/all-events/international-e-waste-day-2019
166 www.statista.com

in order for the energy efficiency of the new device to offset the emissions generated from the production of the previous one.[167]

More than 2 million smartphones were sold in Finland in both 2018 and 2019. Mobile phones accounted for 36% of all home appliance sales and their value was estimated at EUR 900 million in 2018. Globally, the figure was around 1.5 billion phones, half of which were sold in China. The annual sales volumes of smartphones have been in decline in Finland in recent years, which is evidence of the high market saturation rate. The same applies to computers and tablets.

In 2019, the sales of UHD televisions that support higher-resolution 4K image increased by 14% compared to the previous year. The sales of smartwatches in Finland only came to EUR 36 million in 2019, yet still represented year-on-year increases in demand of around 35%. Smartwatches and activity bands are the most common wearable devices. The market for end user device accessories such as headphones, speakers and camera accessories exceeds EUR 100 million and is experiencing intense growth.[168]

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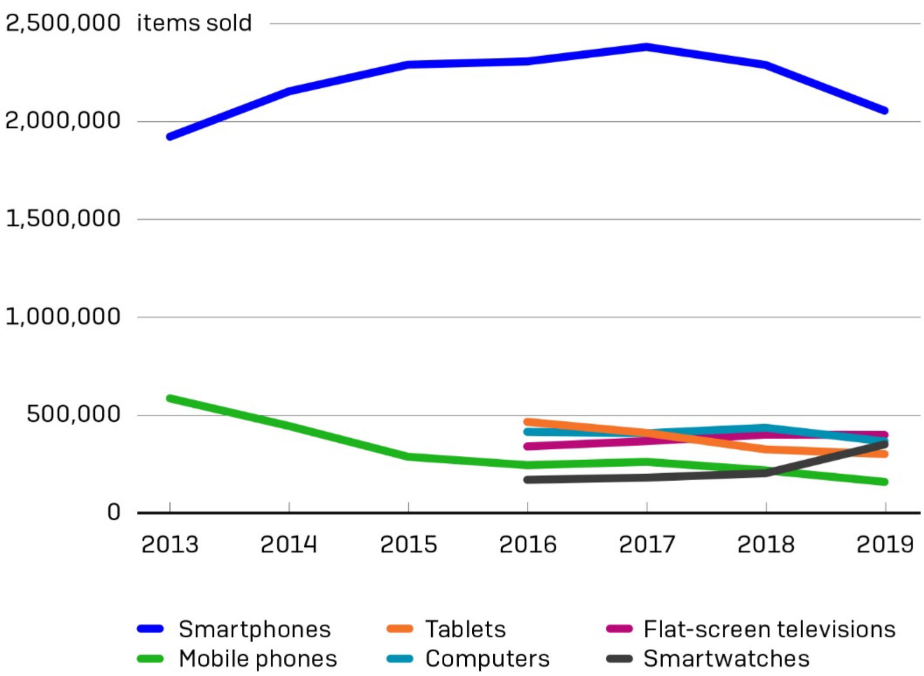
167 European Environmental Bureau 2019: Coolproducts don’t cost the Earth. https://eeb.org/library/coolproducts-report/
168 https://gotech.fi/2020/02/03/kodintekniikan-kauppa-kasvoi-37-prosenttia-vuonna-2019/

Figure 14: Mobile phones considerably outsell all other devices in Finland, but the sales of UHD televisions and smartwatches have increased. Sources: Association of Electronics Wholesalers (ETK), FiCOM, Finnish Environment Institute SYKE.



In Finland, 83% of the entire population and 98% of those aged under 45 use a smartphone. A computer is owned by 87% and a tablet by 54% of all households in Finland. The device most commonly used to access the internet is the smartphone, followed by laptop computers.[169]

Nearly all end user devices (99%) are imported to Finland.[170] While Finland's share of the global end user device market is small, less than 1% in all product groups examined[171,172], in the European frame of reference Finland is a relatively large producer of the rare metals needed for devices. Demand for the high tech metals extracted in Finland may see considerable growth going forward if these are exported to emerging markets.

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[169] http://www.stat.fi/til/sutivi/2019/sutivi_2019_2019-11-07_tie_001_en.html
[170] Nissinen & Savolainen 2019: Carbon footprint and raw material requirement of public procurement and household consumption in Finland – Results obtained using the ENVIMAT-model. Reports of Finnish Environment Institute SYKE.
[171] https://gotech.fi/category/tilastot/
[172] https://www.statista.com/

5.2 Lifecycle of end user devices

Device lifecycle typically begins with raw materials extraction and processing as well as product manufacture. Although product design is not directly related to material flows, it is commonly regarded as one of the lifecycle phases before manufacture. After manufacture, the device ends up with the consumer, who will use it until the end of the product's service life. This lifecycle phase may involve reuse or a second life.

In an efficient circular economy, the technical service lifetime could be followed by the device being remanufactured or its components utilised directly in the assembly of a new device. This is still rare in practice. Once a device reaches the end-of-life phase of its lifecycle and the device or its components can no longer be reused, it is usually taken to collection and recycling. This enables materials recovery for re-utilisation as materials. Some e.g. flammable materials such as plastics can also be recovered for energy production. The worst option is that the device, or its components, end up in final disposal where the materials or their energy content are not utilised again. Recycling involves many challenges, which are discussed in section 5.5.

The environmental and climate impacts of devices can be broken down as follows:

- energy- and water-intensive extraction and processing relating to device material choices
- energy consumption and related climate impacts throughout device lifecycle
- rapid increase in difficult-to-process waste
- recovery of hazardous substances.

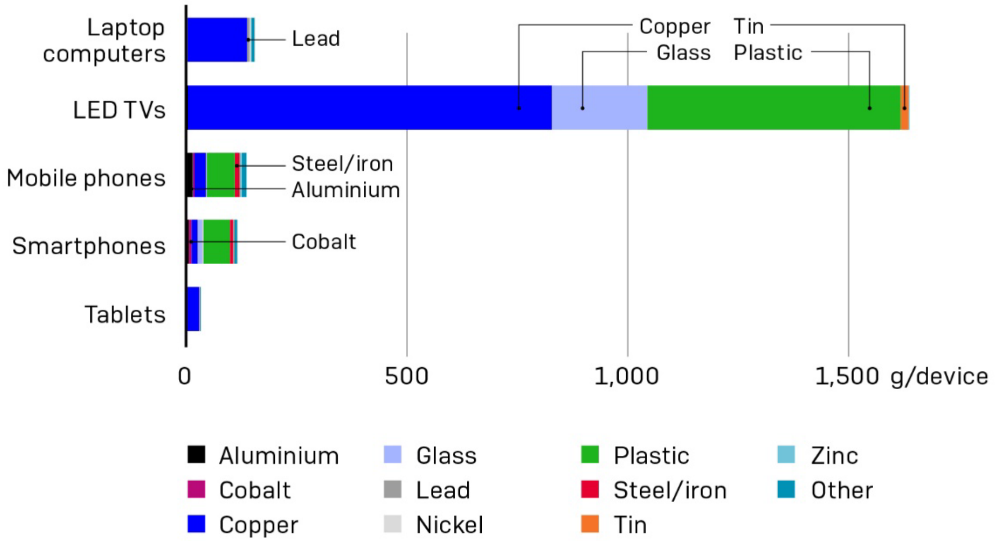
In addition, certain materials involve other sustainability risks, such as poor working conditions and child labour, conflicts and corruption.

5.3 Material flows related to end user devices

The most important raw materials contained in end user devices are metals, plastics and glass. Relatively speaking, the extraction and processing of metals generates greater environmental impacts than plastic or glass, especially in the absence of efficient recycling. For end user devices, the essential metals are silver, aluminium, cadmium, gold, cobalt, chromium, copper, dysprosium, iron, gallium, indium, lithium, magnesium, neodymium, nickel, palladium, praseodymium, platinum, tin, tantalum, titanium, tungsten, iridium, osmium, rhodium, ruthenium, lead and zinc. Increases in the number and size of batteries affect demand for lithium, cobalt, nickel and magnesium in particular. The electronics industry uses significant quantities of precious metals due to their chemical, corrosion-resistance and electrical conductivity properties.[173]

Today's smart devices may contain more than 60 different materials in different quantities and joined in different ways (using glue or screws or as composite materials). End user device functionalities are also being developed further, which sets new requirements for materials and their suitability for the various uses. End user devices have very short innovation cycles, and smart devices in 2030 can be expected to look very different than those we use today. Innovations in the microelectronics domain may also bring about various challenges relating to materials.[174]

Figure 15. End user devices involve extensive use of materials, with only some of these shown in the figure. Source: Finnish Environment Institute SYKE, Cucchiella et al.



In the early years of the 2000s, devices such as mobile phones and related materials needs were characterised by shrinking size and volume, whereas around 2008, the technology process moved from miniaturisation to multifunctionality and effectively turned mobile phones into micro-computers. As regards materials, this meant the use

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[173] Cayumil et al. 2015: Concentration of precious metals during their recovery from electronic waste. Waste Management.
[174] Schischke et al. 2019: The Life Cycle of Smart Devices in 2030: The Effect of Technology Trends and Circular Economy Drivers on Future Products.

of entirely new compounds or metal functionalities. In recent years, the trend has been towards larger display sizes and more durable batteries.

5.3.1 Critical raw materials

Many of the metals used in end user devices are critical raw materials with a high supply risk and a high economic importance. Reliable and unhindered access to these is a concern for European industry and value chains.[175] As regards reducing the risks related to critical raw materials, some potential exists to increase the European production of metals, but enhancing the recycling rates of these metals obviously holds much greater potential. Finland has a producer/supplier role for two metals: cobalt and germanium.

Table 2. Critical raw materials for electronics according to the European Commission (2017), adapted by the Finnish Environment Institute SYKE.

Raw material	Main global producers	Main importers to the EU	Sources of EU supply	Import reliance rate*	End-of-life recycling input rate***
Antimony	China (87%)	China (90%)	China (90%)	100%	28%
Cobalt	Democratic Republic of the Congo (64%)	Russia (91%)	**Finland (66%)**	32%	0%
Gallium	China (85%)	China (53%)	China (36%)	34%	0%
Germanium	China (67%) **Finland (11%)**	China (60%)	China (43%) **Finland (28%)**	64%	2%
Indium	China (57%)	China (41%)	China (28%)	0%	0%
Natural graphite	China (69%)	China (63%)	China (63%)	99%	3%
Tantalum	Rwanda (31%)	Nigeria (81%)	Nigeria (81%)	100%	1%
Platinum group metals	South Africa (83%)	Switzerland (34%)	Switzerland (34%)	99.6%	14%
Rare earth elements	China (95%)	China (40%)	China (40%)	100%	3–8%

[175] COM(2017) 490 final.

5.3.2 Hazardous substances

Electrical and electronic equipment also contains substances that are hazardous to the environment and to human health. These include polychlorinated biphenyls (PCBs), brominated flame retardants (BFRs) and polyvinyl chlorides (PVCs). These substances can be found in e.g. conductor jackets (PVCs), covers and casings of electronic equipment (BFRs) and circuit boards (PCBs).[176]

5.3.3 Finland's primary raw material reserves and their utilisation

Compared with other EU countries, Finland's situation concerning primary raw material reserves is reasonably good. In 2017, there were 9 metal ore mines and 27 industrial mineral mines operating in Finland. The mining of metal ores is currently at its highest level in Finland's mining history.[177] The Geological Survey of Finland (GTK) estimates that the production potential of many critical metals and minerals is good in Finland. As regards lithium, the EU's largest deposits are found in the Ullava-Kronoby area of western Finland.

Demand for precious metals (gold, silver, platinum group metals) required for electronics has also grown. Their exports from Finland over the past 15 years increased by 40–900% in terms of euros. In addition, battery minerals are currently generating a great deal of interest. This interest can be seen especially in the higher number of applications for cobalt and lithium ore exploration permits. Cobalt is currently used especially in lithium-ion batteries, which are present in almost all small electronics. Finland accounts for 66% of the EU's cobalt deliveries, and 13% of the world's cobalt refining takes place in Finland. In addition to mines in Finland, cobalt concentrate is sourced by Finnish refineries from Russia, the Democratic Republic of the Congo (DRC), Austria, South Africa and Germany. Global cobalt production is highly dependent on the DRC, where ethical problems such as the use of child labour have been associated with the production.

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[176] Worrell et al. 2014 Handbook of Recycling: State-of-the art for practitioners, analysts, and scientists.
[177] Vasara 2018: Sector Reports – Mining Sector, Publications of the Ministry of Economic Affairs and Employment 40/2018.

5.4 Energy consumption of end user devices

Modern devices are increasingly energy efficient, but at the same time the number of small devices and home appliances has risen in households. When estimating the energy consumption of the entire ICT sector, the share of end user devices is emphasised, especially if also taking into account consumption during their manufacture.

In-use consumption can be examined either by only taking into account the electricity consumed by devices at the usage location or by taking into account the total consumption arising from the service used with the end user device, i.e. including the energy consumed in data centres and networks. The latter method is appropriate if the aim is e.g. to determine the total in-use energy consumption of a consumer ICT end user device and to employ this data to calculate the carbon footprint (the emission factor used in carbon footprint calculations is different for different countries and also for different services, depending on the routes they use).

These estimates involve a great deal of uncertainties, but the energy consumption of end user devices may decrease slightly in the 2020s due to migration to smaller and more energy-efficient devices.[178] At the same time, the focus in the sector's energy consumption is projected to shift towards data centres and networks.[179]

There is a great deal of variation in end user device energy consumption even within product groups, but some simple assumptions can be employed to calculate indicative results to formulate an overall picture. The numbers of end user devices and expected energy consumption can help produce estimates of the total consumption of product groups.

Among the end user devices examined, televisions are the biggest household energy consumers, even when used only a few hours a day. Televisions are rated in terms of energy efficiency classes, and their annual energy consumption based on 4 hours of use per day is disclosed in the statutory labelling. Today's best-selling televisions typically consume more than 100 kWh of energy per year, the largest in excess of 300 kWh. This calculation only includes direct electricity consumption – not any energy consumption in the network and data centres arising from e.g. the use of Netflix.

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[178] Andrae 2020: Hypotheses for Primary Energy Use, Electricity Use and CO2 Emissions of Global Computing and Its Shares of the Total Between 2020 and 2030. WSEAS Transactions on Power Systems 15.
[179] Pihkola et al. 2018: Energy consumption of mobile data transfer – Increasing or decreasing? Evaluating the impact of technology development & user behavior. ICT4S.

Routers in the home wireless network should also be taken into account in this context, as they are usually in 'on' mode all the time. Compared with e.g. televisions, however, routers are typically low-energy devices. The annual energy consumption of a wireless base station is around 25 kWh.[180] Another device that is continuously switched on but whose own energy consumption is very low is the smartphone, estimated to consume less than 10 kWh per year.[181]

5.5 Reducing environmental impacts of end user devices: spotlight on material recycling

According to a Eurobarometer consumer survey, the most common reasons reported for purchasing a new end user device are that the old device broke, the performance of the old device had significantly deteriorated or certain applications or software had stopped working on the old device. More than half of respondents in Finland report the old device breaking as the reason for getting a new one. A total of 14% had purchased a new device because of new features and services.[182] In mass communication networks, the technological lifecycle of devices is generally long, up to 10–15 years, but the latest services impose new requirements for these receivers, too.[183]

Most European respondents would be ready to use their current devices longer: 64% would like to keep using their digital devices for at least 5 years. Almost 80% of Europeans think manufacturers should be required to make it easier to repair digital devices or replace their individual parts, and a quarter still think this even if it meant that devices cost more. The situation is even clearer in Finland: almost half of the respondents (46%) would be willing to pay more for their device if this made it easier to have it repaired by the manufacturer.

As regards the recycling of devices no longer in use, the biggest obstacles to doing so reported by Europeans are the distance to the nearest recycling point, concerns about

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[180] Sikdar 2013: A Study of the Environmental Impact of Wired and Wireless Local Area Network Access. Consumer Electronics. IEEE Transactions.
[181] Belkhir & Elmeligi 2018: Assessing the ICT global emissions footprint: Trends to 2040 & Recommendations. Journal of Cleaner Production.
[182] European Commission 2020: Attitudes towards the impact of digitalisation on daily lives. Special Eurobarometer 503. Accessed 27 March 2020. https://ec.europa.eu/commfrontoffice/publicopinion/index.cfm/survey/getsurveydetail/instruments/special/surveyky/2228
[183] https://www.testatutlaitteet.fi/ajankohtaista

potential privacy risks and not knowing enough about device recycling processes. For respondents in Finland, the biggest concern was information security: 55% of them were willing to recycle their old devices if they could be certain that this did not pose any potential privacy risks.[184]

Any opportunity for reuse or remanufacturing (recycling components) should be taken before recycling materials as materials. The concepts of ecodesign or Design-for-Recyclability/Circularity aim to strengthen the role of these phases preceding material recycling.[185] These are better alternatives from the environmental perspective as they help avoid many resource-intensive processing phases. Stronger cooperation between the various value chains would help integrate more efficient materials use already into the design phase.

Efficient recycling of waste electrical and electronic equipment (WEEE) reduces the demand for virgin raw materials and therefore decreases climate, water and other environmental impacts from raw materials production. Carbon dioxide equivalent (CO_2e) greenhouse gas emissions from recycled metals are usually much lower than those from metals produced from virgin raw materials, the emissions from which are anticipated to increase further as ore reserves become depleted. At the same time, recycling maintains the value of recycled materials, reduces dependence on imported materials and scarcity of materials in general, and helps avoid the social externalities associated with some metals. The EU continuously strives to increase recycling volumes and the share of recycled material in total materials consumption and also to increase the efficiency of recycling processes.

In Finland, estimates of the volumes of recycled WEEE materials are provided by the national supervisory authority for producer responsibility, the Pirkanmaa Centre for Economic Development, Transport and the Environment. There is no fine-grained data available as regards which consumer electronics categories are the largest in terms of their volumes.

It should be noted that after 2009 the volume of consumer electronics collected from households (recycling points intended for households) and non-households[186] exceeds the volume supplied to the Finnish market. Recovery of materials accounts for the greatest percentage of recycling, with an average of 88% of products going to

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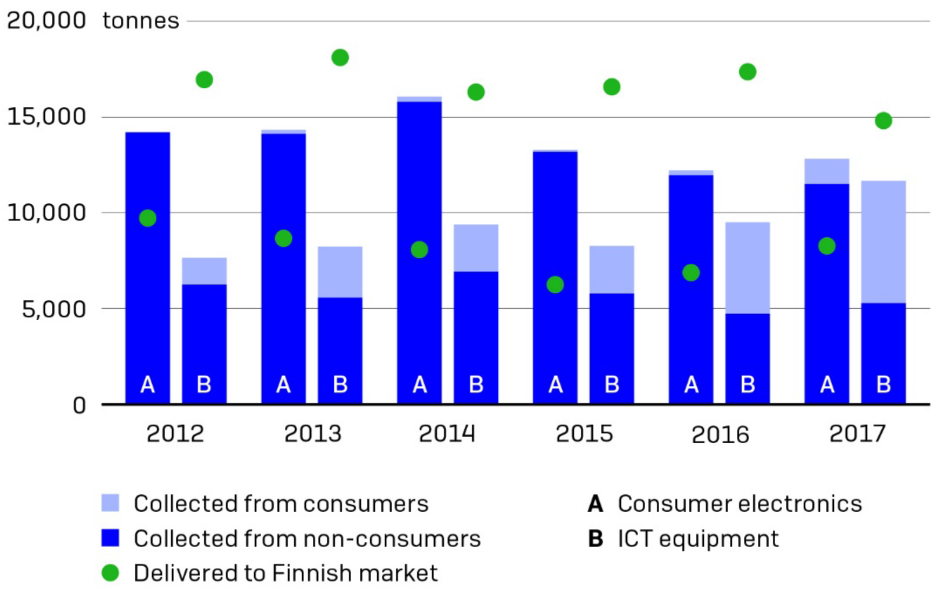
[184] European Commission 2020: Attitudes towards the impact of digitalisation on daily lives. Special Eurobarometer 503.
[185] Bartie et al. 2019: The simulation-based analysis of the resource efficiency of the circular economy - the enabling role of metallurgical infrastructure. Mineral Processing and Extractive Metallurgy.
[186] Estimates of quantities of network devices and components recycled via telecommunications companies and network device suppliers are provided in subsection 4.3.3.

material recycling, around 1% recovered for energy and 10% taken to landfill sites during 2008–2017. The share of reuse (either as whole devices or parts) is marginal (<1%). The bulk of recycled fractions is processed in Finland and a smaller share within the EU. Since 2008, the volume of recyclable consumer electronics exported outside the EU has practically dropped to zero.

All devices taken to official collection points or retail outlets are primarily processed in Finland, at least in the first phase of sorting. Producer communities cooperate with nine Finnish processing facilities as well as with a few reuse or recycling centres and activity centres operated on the basis of pay-subsidised employment.[187]

Figure 16. The recycling of waste electrical and electronic equipment (WEEE) is coordinated in Finland by the Pirkanmaa Centre for Economic Development, Transport and the Environment. The percentage of devices collected from non-consumers is increasing, especially for ICT equipment. These include smartphones, mobile phones, tablets and computers. Consumer electronics includes devices such as televisions, radios and headphones. Source: Pirkanmaa Centre for Economic Development, Transport and the Environment, Finnish Environment Institute SYKE.



5.5.1 Recycling rates

The recycling rates of the metals contained in ICT devices are lower than would be required for their sustainable use. With the current growing demand, sustainable use is a rather challenging goal on the whole, but more efficient recycling could solve at least some of the related challenges. Smart devices need rarer and critical metals,

[187] http://www.serkierratys.fi/

and enabling the recycling of these metals in particular is a possible response to the challenge posed by their rising demand. However, only 1% of rare earth elements are recycled and, overall, the recycling rates of around 35 metals are below 1%. It is difficult or even impossible to ascertain the precise recycling rates. This is due to global chains where raw materials, concentrates, semi-finished products, products and recyclable fractions are transported between countries and continents in rapid cycles.

The recycling rates of home appliances and electronic equipment have been low compared with metals used in buildings, cars or larger equipment (85–90%). However, projections suggest that it is these small devices that will see the biggest future increases in recycling rates. A further challenge to recycling arises from the short lifecycles of these products.[188]

5.5.2 Recycling as a technical process

When ICT equipment is recycled as materials, the recycling process is divided into three main phases: 1) sorting and collection, 2) mechanical pre-processing and separation methods and 3) metallurgical processing, i.e. recovery of valuable materials.

Various technical solutions are available for these three phases in the recycling of ICT equipment. The various solutions all have their technical, metallurgical and environmental pros and cons. In practice, it can be said that the more complex and the more multi-material the product is, the more resources will be required for its recycling and the more metals will be lost during the process – unless the product is a modular one designed for recycling. The technologies used have a major impact on recycling efficiency.

<u>Sorting and collection</u>

Consumer sorting: Recycling begins when the consumer sorts WEEE from their other waste. This affects the efficiency of the entire chain and the recovery of valuable metals. Inefficiency is also caused by any time lag between a device losing its end user value and entering the recycling process.[189] This lag can be shortened by providing financial incentives. Consumer awareness of recycling and recycling points

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[188] UNEP, 2013: Metal Recycling: Opportunities, Limits, Infrastructure, A Report of the Working Group on the Global Metal Flows to the International Resource Panel.
[189] Ibid.

is at a good level in Finland, yet generally speaking recycling volumes could be increased if consumers were to take more products to recycling points.

Collection: WEEE collection takes place through municipal or commercial operators. Globally, WEEE collection may be inefficient, or streams may leak into the grey market or landfill sites.[190] In the EU, extended producer responsibility is mandatory and WEEE must therefore be taken back.

Mechanical pre-processing and separation methods

The purpose of pre-processing and separation is to create suitable (good-quality) fractions for further processing. Recycling can be facilitated through product design.[191,192]

Manual sorting and disassembly: The recycling operator sorts the equipment manually, using visual assessment. Equipment is also disassembled into smaller parts. Manual sorting is used in modern recycling facilities, too, and this improves efficiency in further processing.

Crushing and grinding (shredding): Sorting and partial disassembly is followed by crushing and grinding (shredding) into cleaner fractions. Crushing consumes a great deal of energy, so it is not cost-effective to crush materials into pieces that are too small. Crushing and grinding rarely leads to the complete liberation of recyclable materials, resulting in the generation of some losses at this phase, too.

Separation: Shredded recycled material is full of many dozens of valuable or worthless metals or materials in various forms. For further processing, these fractions must be separated from each other so that each fraction can be steered into the correct further process. Depending on the materials and facility, various methods such as magnetic or gravity separators can be used.

Dust removal: Since dusts may, in relation to their weight, contain a high proportion of valuable metals, such as palladium, gold, copper or rare earth elements, efforts are

[190] UNEP, 2013: Metal Recycling: Opportunities, Limits, Infrastructure, A Report of the Working Group on the Global Metal Flows to the International Resource Panel.
[191] Ibid.
[192] Reuter et al. 2015: Simulation-based design for resource efficiency of metal production and recycling systems: Cases - copper production and recycling, e-waste (LED lamps) and nickel pig iron. Int J Life Cycle Assess 20.

made to recover these.[193] Equipment used for dust recovery includes cyclones, counter-current extractors and suction equipment.

Screening: Screening can be used in different phases, such as separating oversized pieces or otherwise homogenising piece sizes.

Metallurgical processing, i.e. further processing of valuable metals

After pre-processing, fractions that are as pure as possible are transferred for further processing. The purest metal fractions can be melted and sold on. More impure fractions still need further processing through smelting (pyrometallurgy), leaching (hydrometallurgy), refining (hydro- and electrometallurgy) or biometallurgy, or combinations of these.

The choice of technology depends on the quality of the recyclate. Pyro- and hydrometallurgy are often used in tandem, with pyrometallurgy doing the first rough separation and hydrometallurgy producing the final high-quality metals.

5.5.3 Recycling of various types of ICT equipment and components

CRT-LCD, LED displays and televisions	The rapid technological development of display devices is an example of how manufacturing technology affects recycling volumes. The recycling of cathode ray tube (CRT) displays is well-known and profitable, with no significant environmental impacts arising from the process. However, the popularity of LCD and LED displays introduces new challenges to recycling. The recycling of e.g. indium is becoming of value[194]. LED displays contain also gallium, germanium and other rare metals[195], and metals such as gold, copper and silver are present in their circuit boards. Tubes containing mercury require special treatment. In addition, display devices contain plastics that could be recycled better, especially if the recycling of these plastics could be isolated from other plastics so as to prevent hazardous substances ending up in other uses[196].

[193] Marra et al. 2015: WEEE Mechanical Treatments: Effectiveness of Critical Materials. Proceedings of the 14th International Conference on Environmental Science and Technology, Rhodes.
[194] UNEP 2013: Metal Recycling: Opportunities, Limits, Infrastructure, A Report of the Working Group on the Global Metal Flows to the International Resource Panel.
[195] Buchert et al. 2012: Recycling critical raw materials from waste electronic equipment. Öko-Institut (Institute for Applied Ecology).
[196] Eskelinen et al. 2016: Muovien kierrätyksen tilanne ja haasteet [Plastics recycling: situation and challenges]. Clic Innovation.

Laptop computers and tablets	Laptop computers and tablets have been the most valuable WEEE category[197] as their components contain relatively large quantities of valuable metals. In tablets, the largest proportions of valuable metals by weight are present in the LED display and the circuit board due to the compact configuration of the device. From the recycling perspective, the difficulty lies in this compactness. Specific recycling technologies are required to liberate valuable metals. Materials from modern computers show the highest rate of recovery, with up to 99% recycled for reuse in industry.
Circuit boards	Circuit boards are present in a great deal of ICT equipment and account for around 3–6% of the total mass of WEEE fractions. Although the percentage is relatively low, most of the valuable metals are found in these components and, compared with primary ores, their concentrations are considerably higher.[198] A challenge in recycling arises from the complex mix of materials and the physical properties of circuit boards. Circuit boards typically contain more than 20 different metals, which may be bulk metals (copper, aluminium, steel) or valuable metals (gold, silver, platinum), as well as hazardous substances (antimony, arsenic, mercury, lead). Their recycling processes are typically highly energy intensive and involve environmental risks, yet only 30–35% of the metals present in circuit boards can be recycled through these processes. All of the remaining material is typically disposed of.
Smartphones	There are challenges involved in the recycling of smartphones as regards the take-back of old phones. The bulk of old phones tend to be left sitting in people's desk drawers. Whenever these devices are collected for recycling, the recycling process is similar to that of tablets. As the volumes are small, recycling businesses are not very interested in processing these devices. Lithium-ion batteries of smartphones are more potential items for recycling. One of the aspects of interest in battery recycling is the behaviour of cobalt and the possible risks involved, such as release into the air, and relevant regulations.

5.5.4 Recycling challenges

Even though recycling has a positive impact on ICT sector sustainability, the production of recycled materials is not able to respond to the steep increase in product demand. In addition, the interconnectedness of materials in products is often underestimated when examining the recycling of devices.[199]

[197] Cucchiella et al. 2015: Recycling of WEEEs: An economic assessment of present and future e-waste streams. Renewable and Sustainable Energy Reviews.
[198] Cayumil et al. 2015:. Concentration of precious metals during their recovery from electronic waste. Waste Management.
[199] Cucchiella et al. 2015: Recycling of WEEEs: An economic assessment of present and future e-waste streams. Renewable and Sustainable Energy Reviews.

End user devices consist mostly of metals but also contain plastics and glass. In addition to devices typically containing 60% of pure metal components, metals are also present in circuit boards (up to 45 different metals), LCD and LED displays, cables and metal-plastic mixes. Further challenges in their composition are posed by the method of assembly of the various components. For example, screws were still used extensively in the 1990s to join the various parts of phones. Today, adhesives or other once-only methods are increasingly used on components of smartphones or other devices. This makes them difficult to repair and also hampers their pre-processing (disassembly) in recycling.

Comparisons of the weight percentages of materials to their value show that even through materials such as plastic may account for 45% of the weight of a phone, in practice all value comes from metals.

Processing and recovery must be planned and optimised in proportion with access to materials, which varies depending on configuration or product. Optimisation is usually based on financial rationale, i.e. the recycling operator calculates the processing costs in relation to the value of pure metals. Since the value of pure metals may fluctuate strongly over time, the processing parameters are difficult to determine. Process amendments and optimisation unavoidably also affect material flows (the recovery of valuable materials and auxiliary substances used) and the amount of direct or indirect emissions.

The purpose of recycling is to return materials from end-of-life products back into reusable form, i.e. into valuable, pure raw materials that can be easily utilised in new electronic equipment. The recycling of bulk and base metals and components as well as products that only contain one material is already at a good level and resource efficient. Small, complex smart devices are, however, difficult to recycle, as they contain a mix of dozens of different metals, plastics, glass and adhesives. Concentrations of materials may also be very small. The recycling of these products calls for a great deal of resources so that materials can be separated from each other.[200]

Different material mixes may require different types of recycling processes, and some metals used may contaminate substances such as steel or aluminium into an impure form. Current technologies already allow for a relatively high recycling rate if devices are successfully collected for recycling. However, we must be cognisant of the resources (e.g. energy and chemicals) required by the process in proportion to the

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[200] Reuter et al. 2019 Challenges of the Circular Economy: A Material, Metallurgical, and Product Design Perspective. Annual Review of Materials Research.

value of the recycled metal or compared with the environmental impacts of primary materials production.[201]

The so-called carrier metals determine the technical and physical limitations of recycling.[202,203] Carrier metals also enable the recycling of minor metals associated with them. Current electronic products and the various materials they contain have not been designed in accordance with the breakdown of the various carrier metals and the minor metals associated with them. This poses challenges related to recycling optimisation, as many metals are in conflict with each other in terms of recycling technology (i.e. metallurgy). In addition, some important carrier metals are being phased out due to regulation (e.g. lead, due to its health impacts).

Whether simple or complex, all products require a certain amount of primary metals input to improve metal quality, meet increased demand or compensate for process losses. Losses may be significant in recycling.[204] Every recycling phase – in practice every lifecycle phase – results in some degree of loss either in the material itself or its energy content. It is physically impossible to achieve 100% recycling, with regard to either materials or energy, and each cycle involves irreversible losses. Products can be made from 100% recycled materials but, in practice, electronics products can never be fully recycled.[205]

5.6 Future trends in end user devices and opportunities from new materials

New electronics materials are one way of responding to challenges in materials use.

New materials are based on environmentally friendly raw materials sourced from renewable natural resources. These include cellulose-based materials such as paper, cardboard and nanocellulose, which have been identified as suitable substrate materials for electronics in studies conducted by e.g. VVT Technical Research Centre

[201] Reuter 2018: Inconvenient truths of the circular economy. Rethink/Aurubis.
[202] Reuter et al. 2019 Challenges of the Circular Economy: A Material, Metallurgical, and Product Design Perspective. Annual Review of Materials Research.
[203] UNEP 2013: Metal Recycling: Opportunities, Limits, Infrastructure, A Report of the Working Group on the Global Metal Flows to the International Resource Panel.
[204] Bartie et al. 2019: The simulation-based analysis of the resource efficiency of the circular economy - the enabling role of metallurgical infrastructure. Mineral Processing and Extractive Metallurgy.
[205] Reuter et al. 2019: Challenges of the Circular Economy: A Material, Metallurgical, and Product Design Perspective. Annual Review of Materials Research.

of Finland[206,207]. In addition to cellulose-based materials, other compostable or biodegradable materials include bio-based plastics that will break down safely into carbon dioxide and water in a composter or in nature. Compared with cellulose-based materials, bioplastics offer advantages such as better resistance to moisture.

New flexible electronics substrate materials enable the utilisation of energy- and materials-efficient manufacturing methods. Many electronics manufacturing methods are currently based on the removal of material during the process. Flexible materials available in rolls can, however, be used in printing and other roll-to-roll techniques where material is deposited only where it is needed. This way the electronics manufacturing process can also meet environmental requirements without significant material wastage.

The adoption of more environmentally friendly production and product models also generates new business opportunities for existing and new enterprises. Environmental friendliness could be a future competitive asset for the electronics industry, too. Battery manufacturing is one of the significant industries that will benefit from new materials. Most materials for batteries are currently sourced from mines mainly located in Asia, Africa and South America.[208] The concentration of mining and manufacturing on only a handful of countries gives rise to environmental and ethical problems as well as economic and supply risks. Many materials used in batteries are also listed as critical raw materials, such as cobalt used in cathodes and natural graphite used in anodes. New environmentally friendly battery materials such as biochar[209] and sodium-based materials could replace critical materials in many applications. Batteries can also be based on fully renewable materials, which have been developed e.g. in VTT's iBEX programme[210], and can even be made compostable.

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206 www.ecotronics.fi
207 https://www.vttresearch.com/en/news-and-ideas/electronics-developers-start-extensive-co-operation-advance-circular-economy
208 https://ec.europa.eu/transport/sites/transport/files/3rd-mobility-pack/swd20180245.pdf
209 https://finnceres.fi/
210 https://www.vttresearch.com/en/about-us/why-partner-us/vtt-ibex-runway-innovations

6 Software

Digitalisation has transformed markets and business models over the past decade. The most significant element of this transformation has likely been changes in end user behaviour and expectations. Digitalisation has resulted in end users expecting to be able to address their current needs instantly and in real time with the help of different kinds of software. An important market geared to end users has arisen to replace old solutions. Digitalisation has created a real-time, automation-reliant market that builds on technology-based service solutions instead of labour-intensive operation.

Considerable technological advances have been made thanks to digital transformation. End user specificity has given rise to a need for small and independent as well as smart solutions instead of monoliths. Technological advances relating to fields such as artificial intelligence (AI), blockchains, the Internet of Things (IoT) and big data management have enabled the construction of numerous new services that often have market-shaping characteristics.

The rapid pace of digitalisation and technological development moulds the market in ways that may be difficult to predict. Service providers must be able to adapt their services to the needs of different actors with agility. The need to be swift while also creating quality has brought about changes in the structures and operating models of software development organisations. Software development and support is accomplished with less human resources than before, new software versions are constantly being rolled out and deployment takes little time due to automation. Such an operating model enables fast and controlled quality assurance on the part of the software developer. The availability of general functionalities as open source code has increased the efficiency and speed of software development.

Software plays an important role in today’s society as an enabler of digitalisation. Software works as an integral element of equipment and processes. Software provides the tools to process the data generated by datafication while at the same time generating new data. Even though software is always tied to a specific platform and devices, a lifecycle extending from production through use to decommissioning can be identified for software as well. The climate and environmental impacts of software, as an intangible product, are nonetheless mainly visible in production and use. Assessing and influencing these impacts in software engineering has not yet gained wide consideration.

6.1 Software footprint and handprint

The (environmental) impacts of IT software can be understood from two different perspectives: the footprint and the handprint. Software footprint relates to the direct impacts of software, including the resources required for software engineering and in-use energy consumption, whereas the handprint is to do with (indirect) benefits obtained through software. The handprint is a somewhat novel way of describing the positive climate impacts of one sector on another. To be more specific, the handprint can be determined by deducting the solution's own footprint from the benefits obtained.

The impacts of software can also be assessed in terms of their greenness and sustainability. 'Greenness' refers to the efficient production and energy-efficient use of software code, while 'sustainability' refers either to software being usable for a long period of time (service life) or software having positive impacts relating to the UN Sustainable Development Goals (SDGs) (social, ecological, economic and cultural sustainability).

Below, the former feature is referred to as 'longevity' and the latter as 'sustainability'. The term 'greenness' is used to refer specifically to environmental impacts (ecological sustainability). Longevity often generates both greenness and broader sustainability. For example, software of high longevity needs to be replaced less frequently and is therefore likely to generate lower costs than software with a short service life. Ideally, all of the perspectives are included simultaneously: the software has been designed effectively as green, minimising the energy required to run it and increasing process efficiency, as well as sustainable, promoting the various SDGs with high longevity.

Table 3. Environmental footprint and handprint of software development.

	Footprint	**Handprint**
Software engineering	• Resources required for engineering (hardware, development environments) • Engineering efficiency (greenness)	*)
Software use	• Software energy consumption • Software efficiency (greenness) • Software longevity (service life)	Software impacts on UN Sustainable Development Goals (SDSs) (sustainability)

***) As a rule, the production of ICT solutions (incl. software) does not represent obtainable benefits. Benefits can only be seized through use.**

The following discusses the components presented in the table in greater detail based on knowledge available from the literature, starting from software engineering and then covering software use and its various perspectives.

Like engineering in general, software engineering follows whichever processes are popular at the time. The current popular trend is to use various agile software development methods instead of the earlier waterfall models. Regardless of the method employed, greenness and sustainability must be taken into account in software development. Greenness and sustainability were introduced to software and software processes around 2010[211,212,213], mainly as the idea of understanding what sustainability means from the software perspective and especially what the impacts of sustainable development perspectives and stakeholders are on this sustainability.[214] Very soon, the software sustainability perspective expanded into the notion that sustainability and greenness should be seen as software quality criteria[215,216] and therefore as part of requirements specification.[217,218,219,220] This notion has given rise to both detailed processes where the aim is to integrate sustainability requirements into development work [221] and into high-level declarations on how sustainability should be taken into account in the software process[222]. In addition to requirements specification, the sustainability of software has been examined from the viewpoints of software architecture and maintainability.[223] The focus in software sustainability and greenness is clearly on the initial phases of the development process where the right choices can help ensure software longevity (service life/technical durability) and greenness.[224]

In addition to the software engineering process, attention must be paid to the output – the code. Modern approaches based on software development environments and agile methods aim for the speedy release of code rather than for the code running efficiently (greenness). On the other hand, current development environments do not

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211 Dick et al. 2010: A Model and Selected Instances of Green and Sustainable Software. What Kind of Information Society? Governance, Virtuality, Surveillance, Sustainability, Resilience. Springer.
212 Naumann et al. 2011: The GREENSOFT Model. Sustainable Computing: Informatics and Systems.
213 Kern et al. Green Requirements Engineering with the GREENSOFT Model Taking the whole Lifecycle of Software into Account.
214 Lago et al. 2013: Leveraging “Energy Efficiency to Software Users”. GREENS/ICSE.
215 Lago et al. 2015: Framing Sustainability as a Property of Software Quality. CACM.
216 Condori-Fernandez & Lago 2018: Characterizing the contribution of quality requirements to software sustainability. JSS.
217 Becker et al. 2016: Requirements: The Key to Sustainability. IEEE Software.
218 Venters et al. 2017: Characterising Sustainability Requirements. SEIS/ICSE.
219 Seyff et al. 2018: Tailoring Requirements Negotiation to Sustainability. RE.
220 Seyff et al. 2018: Crowd-Focused Semi-Automated Requirements Engineering for Evolution Towards Sustainability. RE.
221 Penzenstadler et al. 2018: Everything is INTERRELATED: Teaching Software Engineering for Sustainability. SEET/ICSE.
222 https://www.sustainabilitydesign.org/
223 Venters et al. 2018: Software sustainability: Research and practice from a software architecture viewpoint. JSS.
224 Karita et al. 2019: Software industry awareness on green and sustainable software engineering: a state-of-the-practice survey. SBES.

support the development of energy-efficient code either[225] if energy efficiency is not taken into account in the software libraries utilised in the development environment or if the operating system fails to support efficient execution.[226] This in turn is challenging, as there are so many different code execution environments.[227]

The execution environment and context also pose a challenge in measuring software energy efficiency. Generic metrics[228] do not yield precise results but, on the other hand, it is not easy to create a generic measurement environment, either.[229,230] Software energy measurement therefore typically takes place in a very limited context[231], which makes the results non-comparable.[232] A further challenge is posed by the use of numerous different metrics.[233]

The research literature presents a variety of sustainability tools and indicators for software development. It is particularly important in software development to continuously monitor and analyse these indicators and use them to set sustainability objectives for the next version of the software to be released. Assessments of the greenness of software can be based on variables including the following: customisability, reuse[234], portability, light maintenance needs, performance, reliability, usability, predictability, efficiency and footprint monitoring. Some of the variables deliver environmental savings in the development phase, some in use and some in maintenance.[235] They primarily strive to make use and maintenance efficient so as to avoid unnecessary energy demand while also extending the service life of the application and devices.

Practices that have empirically been found to improve software energy efficiency in contexts such as search engines include query optimisation. The databases behind search engines usually perform heavy and complex data organisation and indexing

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225 Capra et al. 2012: Is software "Green"? Information and Software Technology.
226 Ardito & Morisio 2014: Available data and guidelines for reducing energy consumption in IT systems. Sustainable Computing: Informatics and Systems.
227 Jagroep et al. 2016: Extending software architecture views with an energy consumption perspective. Computing.
228 Taina 2010: How green is your software? ICSB.
229 Johann et al. 2012: How to Measure Energy-Efficiency of Software: Metrics and Measurement Results. GREENS.
230 Ahmad et al. 2015: A Review on mobile application energy profiling: Taxonomy, state-of-the-art, and open research issues. JNCA.
231 Christea 2017: Energy Consumption of Applications on Mobile Phones, M.Sc. Thesis. LUT.
232 Temesgene 2016: Cyber foraging for green computing, improving performance and prolonging battery life of mobile devices, M.Sc. Thesis. LUT.
233 Bozzelli et al. 2014: A SLR on green software metrics.
234 For the reuse of applications and their components, see e.g. Radu, 2018: An Ecological View on Software Reuse. Informatică Economică 22:3.
235 Albertao et al. 2010: Measuring the Sustainability Performance of Software Projects. IEEE 7th International Conference on E-Business Engineering.

that may increase search efficiency but do so at the expense of energy efficiency. Another good practice is using a “sleep” function to put software or a process or main thread in sleep mode for a specific period of time. A process that is in sleep mode will not continue and will therefore not consume energy e.g. at night or during the execution of another process.[236]

The final output of the software engineering process is software code relating to an application domain that is run in the intended execution environment (e.g. mobile device, data centre). As mentioned above, the sustainability of this output can be seen as the longevity, resilience or reusability of the software product or as indirect sustainable impacts in the application domain. The longevity of a software product depends on one hand on the choices made during the production process and on the needs of the application domain on the other. Current mobile applications are typically more short-lived than previous desktop applications or mainframe computer software. The short life of software is not necessarily due to inefficient software implementation but rather due to changing consumer needs. This field specialising in software design has been studied extensively also from the sustainability perspective.[237,238]

Indirect impacts in the application domain are also difficult to measure, partly due to the complexity of measurement and partly due to rebound effects. Metrics other than energy consumption are often used to measure the indirect impacts of software[239], which makes impact assessments more difficult. Software rebound effects[240] also bring negative impacts alongside the positive impacts that are usually examined, which also makes it harder to assess the impacts of software, especially when not only talking about impacts relating to energy use.

While sustainable software engineering has been studied and developed for almost a decade by now, there remains plenty of scope for further research. To date, financial considerations have constituted the biggest barriers to commissioning sustainable as well as climate and environmentally friendly software. Although green coding saves the client’s resources, greenness may also involve various certification requirements, limit the formation of production chains or result in more expensive solutions. Unless the client is pursuing a specific green image, the climate and environmental friendliness of programming is currently best promoted by environmental requirements

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[236] Procaccianti et al. 2016: Empirical evaluation of two best practices for energy-efficient software development. Journal of Systems and Software 117.
[237] Blevis 2007: Sustainable Interaction Design: Invention & Disposal, Renewal & Reuse. CHI.
[238] Baumer & Silberman 2011: When the Implication is not to Design (Technology). CHI.
[239] Duboc et al. 2019: Do we really know what we are building? Raising Awareness of Potential Sustainability Effects of Software Systems in Requirements Engineering. RE.
[240] Coroama & Mattern 2019: Digital Rebound – Why Digitalization Will Not Redeem Us Our Environmental Sins. ICT4S.

laid down in legislation.[241] The quickest way towards energy efficiency in software services is to put a price on energy consumption when billing for a service.[242] Poor awareness of the sustainability impacts of software is also a contributing factor. Increased awareness affects user application choices, needs and impacts expressed by customers, producers' sustainability values, and tools and quality criteria employed by application developers. By influencing the relevant leverage points, change can ultimately be achieved throughout the chain.[243]

6.2 Cloud services and Software as a Service (SaaS)

Software service models have evolved in response to the dynamic and changing needs and expectations of the market. Instead of big, often licence-based monolithic one-stop-shop solutions (servers + networks + software), customers and service providers alike have started migrating to Software as a Service (SaaS) approaches. SaaS as such imposes no restrictions as to whether the services are provided from the customer's own data centre, the service provider's own cloud or a public cloud. Instead, SaaS enables the capacity of the service to be used from any source desired.

SaaS models where the service provider has overall responsibility also for the cost structure of the service, including the computing power to run the software, provide incentives for energy efficiency as well. It must be recognised that many digital service portfolios consist of numerous discrete programs, and the total energy efficiency of the service is more difficult to manage in such a case. Nonetheless, the same incentive is present.

Existing software will not necessarily become more energy efficient or environmentally friendly simply by putting it in a service provider's cloud. The carbon footprint of running the software in such cases depends wholly on the greenness of the service provider's supply of electricity, as the energy footprint of running the software remains a constant. However, computing power can be dynamically distributed for running software, which may considerably reduce the footprint of software run at infrequent intervals. On the other hand, the business using shared cloud services may perceive

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[241] Penzenstadler et al. 2014: Infusing Green: Requirements Engineering for Green In and Through Software Systems. TechReport UCI-ISR-14-2.
[242] Hindle 2018: If you bill it, they will pay: Energy consumption in the cloud will be irrelevant until directly billed for. RE4SuSy.
[243] Penzenstadler et al. 2018: Software Engineering for Sustainability - Find the Leverage Points! IEEE Software.

such use as environmentally friendly indeed. After all, it eliminates the need for their own servers.

Public cloud services have grown in popularity in the past decade. For a large part of the customer and service provider base, generating their own capacity has not been tempting or commercially sensible. Public cloud service providers benefit significantly from the centralised management of capacity and the investment synergies required by considerable volume demands.

Globally, the trend is towards a majority – though not all – of the required cloud service capacity being largely provided by only a few public cloud service providers.[244] However, it should be recalled that using public cloud capacity and services is not cost-effective or energy efficient in and of itself. Efficiency and effectiveness can only be achieved when the capacity of public cloud services is used dynamically, according to need. In such a case, the costs are directly proportionate to the needs for and the use of the services. The carbon footprint of a service migrated to the cloud is also wholly dependent on the geographical location where the software computing power is generated.

Many businesses take up public cloud capacity and services for both internal development needs and external production needs. Concerns and regulation relating mainly to the physical data storage location will cause production needs in particular to be divided between public and private cloud solutions. What is important is that product development can simultaneously support production from both public and private clouds in a controlled manner. Over the past five years or so, the use of e.g. container technologies and orchestration has seen considerable increase. Such technologies (for example Docker and Kubernetes) aim to eliminate dependencies on the application's underlying operating system and infrastructure services. Further expansion is likely to be seen in similar developments, which will lead to greater efficiency in cloud service capacity management.

Recent arrivals on the scene include Web 3.0 and peer-to-peer (P2P) technologies in particular. These new approaches deliberately seek to move away from traditional cloud service utilisation to rely instead on the storage space and computing power held by users. For the time being, the energy efficiency of solutions such as these can only be guessed at.

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[244] TietoEVRY 2020.

7 Key emerging technologies in view of climate and the environment

The technologies examined in this chapter are often the focus of attention when it comes to digitalisation and the paradigm shift in services and activities. R&D into these technologies has increased at an accelerating rate in recent decades and the number of practical applications for e.g. industry and consumers has grown. The exception here is quantum technology, which is still at the R&D stage. Its practical applications are only expected in the near future.

Research data on how the impacts of ICT sector technologies on climate change and the environment will develop over the next 10–20 years is as yet available only to a very limited extent. Therefore their applications in the Finnish context and the impacts of such applications on climate and environmental change also cannot be assessed with accuracy. Applications also often have an indirect effect on human behaviour and actions, which adds further uncertainty to any forecasting of impacts.

All the ways in which technology is applied in society have some impact on climate and the environment. In principle, the development of ICT technologies is not necessarily guided by sustainable development goals or environmental values but rather by the desire to enable a given activity or to make it more efficient. When applying technology, it is important to consider also the ultimate utility of the application to society as well as the impacts on climate and the environment arising from the application. From society's point of view, it would be most advantageous to prioritise the use of ICT for those applications that are proven to have as wide as possible positive impacts on society also in terms of climate and the environment, taking into account also the indirect effects of the application on changes in behaviour and actions.

The two issues vital to climate and the environment in respect of the new ICT technologies examined are the consumption of energy and the use of materials. Increasing the share of low-emission electricity in the grid and improving the energy efficiency of equipment are direct ways to reduce the negative climate impacts of technologies. The volume of technology use, the application itself and the manner of applying the technology determine whether the climate and environmental impacts created with the technology are ultimately positive or negative, and also the extent to which this occurs. Applications with a positive impact on increasing zero-emission energy production and the circular economy will contribute to the discovery of solutions.

The emerging technologies now examined are also underpinned by two key support technologies that affect not only the development of technologies but also their climate and environmental impacts. These support technologies are 5G and cloud services. The majority of new applications rely on fast and high-performance connectivity. In mobile networks, this development is currently expressed by 5G and, in fixed networks, by optical fibre. A feature common to emerging technologies is the rising volume of data. Since data storage and processing to an ever increasing extent require storage capacity and computing power, making use of cloud services often provides the easiest and most flexible and cost-effective solution. The following sections describe the development of the six emerging technologies identified by the working group as key, the development of their applications, and their foreseeable climate and environmental impacts. The analysis of potential impacts is based on the study commissioned from Deloitte by the Finnish Transport and Communications Agency Traficom.

7.1 Artificial intelligence, algorithms and machine learning

Artificial intelligence (AI) is an area of computer science that focuses on the creation of programs and mechanisms that can show behaviours considered intelligent. AI enables systems that mimic human thinking and, in some cases, are also capable of reasoning and learning. AI is based on the performance of pre-determined tasks based on AI programmed logic – such AI is called narrow AI. General AI refers to software or machines that are capable of solving any intellectual problem. However, general AI has not yet been developed; all of today’s AI is narrow AI.

AI works on the basis of algorithms, i.e. rules or procedures formulated in a finite and sequential order which provide detailed instructions on how a task or process is performed. Algorithms are often very long and complex and contain repetition and logical deduction. With algorithms, AI can be directed to solve a given, precisely defined problem. Types of common algorithms include search algorithms, sorting algorithms and selection algorithms.

Machine learning is one of the key subfields of AI. The purpose of machine learning is to make AI work even better on the basis of user action or initial data. In machine learning, a procedure, i.e. an algorithm, is typically not determined for all situations and, instead, the AI independently learns how to arrive at the desired result. The difference between machine learning and traditional AI is that machine learning does not seek to mimic human behaviour but to recognise in large data sets patterns that are beyond human recognition capability. Machine learning also encompasses deep learning, which roughly imitates the workings of the human brain in learning based on neural networks.

The technologies in this field are already used in Finland to a fair extent. Applications include data collection in support of decision-making, person identification and monitoring of buying behaviour. AI, algorithms and machine learning play an important role in the smartification of society, in predicting human behaviour and the behaviour of nature, and in increasing the efficiency of production and activities. The technology also promotes resource wisdom and distributed generation.

From the perspective of climate and environmental impacts, the most important applications of AI are smart buildings, the smart grid, smart circular economy, forecasting and observation, influencing the behaviour of individuals, and smart production systems and processes. Finland has recognised the potential of AI also in the enhancement of public services. The national AuroraAI programme will make use of AI to create models that can drive forward the best public administration in the world. The aims of the programme include improving the match between users and public services while tackling inefficiency and resource waste.[245]

AI can also be utilised to improve the energy efficiency of the ICT sector itself, for example to optimise the energy consumption of modern data centres. Telecommunications company Elisa has developed mobile network control and operation automation solutions based on machine learning. These have been estimated to deliver savings of up to 14% in network energy consumption.

AI applications also include ones with negative climate and environmental impacts, however. AI is forecast to hold significant potential in promoting the extraction of fossil fuels and improving the efficiency of extraction through means such as field operation analysis, troubleshooting and improved reserve modelling. With digital solutions, the volume of recoverable oil and gas reserves could be increased by 5%.[246] The decisions of society on the applications of emerging technologies play a major role in the indirect impacts of these technologies on climate and the environment, and on sustainable development in the broader sense.

The collection and processing of data stand at the heart of technology. Subject to ongoing development, machine learning and deep learning require specialised equipment. The equipment required to develop and train machine learning or deep learning models consumes substantial amounts of energy for weeks or months on

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[245] https://vm.fi/tekoalyohjelma-auroraai
[246] IEA (International Energy Agency) 2017: Digitalization and Energy. Technology report.

end. It has been estimated that the majority of emissions from machine learning and deep learning occur specifically at the development, programming and training stage.

The training of a single language-learning model generates the same amount of carbon dioxide emissions as a trans-American flight. In terms of emissions, the use, development and training of an advanced language-learning model would be equivalent to 39 trans-American flights.[247] According to another study, the lifecycle carbon footprint of training a deep learning AI model may be up to five times the lifecycle emissions of the average American car.[248] To date, this downside of the smartification of society has received quite little attention. In addition, smart measurement requires a great deal of various kinds of electronics and equipment that in time becomes electronic waste.

The table below presents a compilation of the projected climate and environmental impacts of AI, algorithms and machine learning.

Table 4: Possible climate and environmental impacts of AI, algorithms and machine learning.

Positive	**Negative**
• Optimising energy consumption and promoting the use of renewable energy sources (smart buildings, power grid) • Reducing the use of virgin materials and ancillary impacts; smart circular economy and demand forecasting • Data promotes resource wisdom and material efficiency	• Material requirements and constant energy consumption of technical measuring equipment • May slow down exit from fossil fuels by facilitating their extraction • High energy consumption in training AI models

7.2 Blockchains and their applications

Blockchain is a technology that allows unconnected parties to jointly produce and maintain databases in a wholly distributed manner. Technically speaking, a blockchain is a ledger or log of transactions distributed among the blockchain participants, which allows transactions to be verified from multiple sources and compiled into a database. In other words, a blockchain is a distributed and transparent database that is not owned or controlled by any single entity. The distribution makes the data in the blockchain virtually impossible to manipulate. One

[247] Strubell et al. 2019: Energy and Policy Considerations for Deep Learning in NLP. The 57th Annual Meeting of the Association for Computational Linguistics (ACL).
[248] Strubell et al. 2019: Energy and Policy Considerations for Deep Learning in NLP.

of the key benefits of blockchains is that they eliminate the need for third-party independent verifiers of transactions. Blockchains allow databases to be maintained with transparency and without administrators.

The first major practical blockchain application was designed in 2009 for the Bitcoin cryptocurrency. Blockchain technology is still relatively new, however, and its application areas are still expanding. At present, the technology is used in sectors including finance, digital housing trade, and tracking the origin and transport of goods in the field of logistics. A few larger blockchain networks have been established in Finland by multiple actors to identify and develop blockchain-based solutions. Both structural changes in the functioning of society and how to ensure trust in digital transactions and solutions to the problem of the high energy consumption of open blockchains will be required if blockchains are to become more prevalent in Finland. From the climate and environmental impacts perspective, the most important blockchain application areas include direct peer-to-peer trade, solutions provided to e.g. logistics by transparency and reliability, and finance.

Blockchain technology allows individuals to engage in peer-to-peer trade transparently and reliably with no intermediaries. The technology may indeed play an important role in distributed generation. Peer-to-peer trading of renewable energy would allow households and housing companies to sell the excess energy they produce directly to other consumers via a blockchain platform. This could incentivise households and housing companies to build renewable energy production solutions.

Blockchain technology can significantly foster transparency and reliability in supply chains and in the activities of businesses. The use of tracking and certification to promote sustainable mining is one possible application that could contribute to the responsibility of the entire technology sector. Mined raw materials can be provided with digital fingerprints that allow a blockchain to be used to reliably track the raw materials across the entire supply chain.

Blockchain technologies can also be used to verify the authenticity of renewable energy certificates. Such authentication accomplished with blockchain technology would boost confidence on the part of buyers and eliminate the need for third-party certification. Corporate responsibility reporting and data could also be verified with greater ease and accuracy by using blockchain technology.

Blockchains could additionally streamline financing processes, which for businesses, for example, could result in the faster development and introduction of sustainable innovations. Blockchain-based cryptocurrencies have appeared alongside traditional currencies, but as yet their use is quite limited.

‘Mining’ is also a concept associated with cryptocurrencies. The technical objective of this mining is to ensure the immutability of cryptocurrency transactions and to create a permanent chronological transaction ledger. The computing power required to add a block to the chain can be adjusted by adjusting the terms; this is also referred to as ‘difficulty’. A blockchain will adjust the difficulty of blocks at pre-determined intervals – in other words, the degree of mining difficulty changes according to the aggregate computing power of miners. Consequently, mining calls for high computing power and mining farms comprising large numbers of computers have been set up expressly for this purpose. Mining is popular because it allows users to earn cryptocurrency in reward for mining.

A clear negative aspect associated with blockchain technology is the high energy consumption required for the related computing. This presents a particular challenge in public global blockchains such as Bitcoin. At the current stage of development, the energy consumption of such wide-scale public blockchains is so high that even the most positive applications in terms of climate and the environment may have negative net impacts. In addition to public global blockchains, blockchain technology can also be leveraged through private permissioned blockchain platforms. On such platforms, only certain validator nodes hold write access rights to modify the blockchain. Permissioned blockchain platforms may be considerably more energy efficient that public ones, and may contribute to solving the energy consumption problems typical of blockchains.[249]

Table 5: Possible climate and environmental impacts of blockchain technology

Positive	**Negative**
• Increased use of renewable energy sources and peer-to-peer trading • Sustainable and responsible production and reporting as well as transparency and reliability of value chains • More straightforward financing can lead to the faster development and introduction of sustainable innovations	• At the present stage of development, the energy requirements of blockchain technology may make many applications climate-negative • More straightforward financing can lead also to the faster development and introduction of applications that are harmful in terms of climate and environmental change

[249] Andoni et al. 2019: Blockchain technology in the energy sector: A systematic review of challenges and opportunities.

7.3 Robotics and autonomous systems

Robotics is the science of designing, creating and using robots. Robots can perform tasks traditionally performed by humans with either full or partial autonomy without any human interaction even by means of equipment or machinery. Autonomous systems are systems and software functioning in a similar manner. Key applications of these technologies include industrial robots, collaborative robots or ‘cobots’, software robots, transport and logistics applications, and consumer robots.

Of these, industrial robots in particular have long been used in various sectors of industry. The more recent incarnation of industrial robots is the cobot, a robot that collaborates with humans in industrial production. Where industrial robots are usually very large in size and unwieldy, cobots are designed for smaller size and greater sensitivity. Besides manufacturing, also many other organisations use robotics in the form of robotic process automation (RPA) used to automate certain routine processes in knowledge work that used to be performed by humans. RPA relies on information systems and is based on either a pre-determined workflow or AI-based self-learning software.

Robotics and automated systems are already widely used in Finland, especially in industry. Their use is expected to increase further as the prices of production systems level off, because the technology boosts the efficiency of production processes and reduces waste in production. The technology is evolving at a rapid pace, which opens up more and more new and increasingly complex applications. Next-generation robots make use of AI, algorithms and machine learning, which allows them even to replace humans in certain operations. However, it should be noted that each robot and system requires energy to function, while the equipment requires new materials.

From the climate and environmental impacts perspective, the most important application areas for robotics and autonomous systems are transport and logistics, in which fields both robotics and automatic and autonomous systems are projected to be a central element in the transport systems of the future. Intelligent transport, transport automation and its evolution are described in more detail in subsection 8.1.2 and logistics solutions in section 9.1. In addition, robotics and autonomous systems are expected to deliver positive climate and environmental impacts in the areas of automatic production systems and processes, more efficient detection, assessment and response, and carbon capture and storage (CCS).

In transport and logistics, the use of e.g. unmanned and automated drones to deliver goods could potentially reduce the number of delivery vehicles on roads especially in urban areas.[250] The use of drones in delivery services is still at the experimental stage. Considerable challenges arise from the size and weight restrictions on the goods delivered, the use of wide-ranging communications links required to fly drones beyond line of sight, and developing the flight control system.

Studies indicate that the positive climate impacts of robotics and autonomous systems in transport and logistics, such as the reduction in freight transport emissions, are limited and dependent on context[251] and also on the progress made in other environmental and climate actions such as electrification and the sharing economy. Moreover, transport volumes may rise unexpectedly and the decentralisation of logistics, for example, may lead to an increased need for materials and energy.[252]

Robotic logistics can also be utilised by businesses as an in-house logistics tool. The technology can supplant work traditionally performed by humans, such as goods handling, reception and sorting in warehouse settings.[253] Robotics can also be utilised in the automation of various types of non-road mobile machinery, for example in agriculture, and also in other sectors. In these situations where robotics is utilised, savings can be achieved in the costs and emissions of lighting and air conditioning, for example. Again, the impacts depend on the application: when an autonomous system introduces greater efficiency to activities such as coal mining, the impacts on the environment are negative.

Robots such as advanced drones can also be used for detection, assessment and response. They allow observations to be made and action to be taken in hard-to-reach locations.[254] Electricity grid inspections, for example, can be carried out by drone, and maintenance also performed without any travel. Specially equipped drones also allow us to obtain an entirely new view of nature and its state. Robotics can also be utilised in the assessment and monitoring of the underwater environment. Technologies therefore deliver new tools to research into and monitoring of climate and the environment.

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[250] IEA (International Energy Agency), 2017: Digitalization and Energy. Technology report.
[251] Goodchild & Toy 2017: Delivery by drone: An evaluation of unmanned aerial vehicle technology in reducing CO2 emissions in the delivery service industry. Transportation Research.
[252] Stolaroff et al. 2018: Energy use and life cycle greenhouse gas emissions of drones for commercial package delivery.
[253] GeSI (Global e-sustainability initiative) & Deloitte 2019: Digital with Purpose - Delivering a SMARTer 2030.
[254] IEA (International Energy Agency) 2017: Digitalization and Energy. Technology report.

Several technologies and devices are under development internationally that, going forward, could allow carbon capture and storage directly from the atmosphere, for example by means of robots that emulate trees.

Table 6: Possible climate and environmental impacts of robotics and automated systems

Positive	Negative
• Automation and optimisation in freight transport and in-house logistics generate cost-effectiveness and lower emissions in deliveries • Remote maintenance and monitoring extends equipment lifecycles • Using robots to measure environmental impacts helps assess the state of nature and produces material for environmental research and consumer communications • Carbon sequestration	• Energy consumption and material needs of robots and autonomous systems • Possible increase in transport with automation leads to rising energy consumption • Decentralisation of warehousing facilities due to drone deliveries increases material requirements and energy use on premises • Greater efficiency in and facilitation of coal mining, for example, may slow down the phasing out of fossil fuels

7.4 Quantum technology

Quantum technology means the controlled utilisation of the principles of quantum mechanics, such as quantum entanglement and quantum superposition, in practical devices, processes and computing. Quantum technology enables the development of quantum computers and quantum computing, for example.

While the quantum computer is still under development, it is expected to deliver a solution especially to computational problems that would take classic computers an exceedingly long time to accomplish. In this context, computational problem refers to a problem that has a simple answer but a huge number of possibilities to go through. The higher computing power of the quantum computer over the traditional computer lies in that the ordinary computer memory stores information as binary states, whereas quantum memory stores a quantum state, i.e. in all possible combinations at the same time. The quantum computer will never fully supplant the classic computer, as it is not equally suited to all kinds of computing, but in the future the quantum computer may play a major role in computing relating to optimisation and simulation, for example.

Besides incomplete development, there are also other factors that slow down the rising prevalence and use of computers making use of quantum technology. In practice, using and controlling a quantum computer is highly demanding, as the temperature of the space in which the computer is used and the computer’s own internal interactions easily interfere with the computing. Because of this, quantum computers are typically used at a temperature close to absolute zero. For the time being, quantum computers are also very expensive to build. Due to these challenges, estimates vary as to the wider availability of quantum computers. According to some estimates, quantum computers could be but a few years away, while others put the time at a few decades. Nonetheless, recent years have seen considerable leaps in development and innovations that advance the entire field.

The climate and environmental impacts of quantum technology are perceived as mostly positive, as the technology makes problem-solving faster and more energy efficient. The environmental impacts of quantum computer construction or administration do not essentially differ from those of similar equipment, so these phases do not give rise to any considerably greater emissions than is the case with current technology. Quantum technology could provide a solution to issues such as ICT sector energy consumption. It should be chosen to be applied only in cases where an ordinary computer cannot reach the solution with the same efficiency.

More specifically, the most important applications of quantum technology in view of climate and environmental impacts include increasing the efficiency of AI, algorithms and machine learning by means of high-performance computing, which would improve planning in industry and transport, impact model calculation and forecasting. Quantum technology also enables breakthroughs in carbon-intensive processes.

The rising computing power provided by quantum technology enables more efficient AI and algorithms and, consequently, facilitates the calculation and forecasting of advanced emission and climate impact models in respect of matters such as traffic volumes, the need for different forms of mobility and journey times in travel chains. This can help prevent congestion in urban traffic, cut waiting times and make traffic flows smoother. Higher computing power greatly increases the accuracy of predictive models, and capacity can also be utilised to calculate emission and impact models for various processes.

Quantum technology enables highly efficient molecular modelling, which in the current view will lead to several breakthroughs in the development of carbon-intensive processes already within the next ten years. This will allow the climate-cleaner production of substances such as ammonia and hydrogen. A fall in the cost of manufacturing green hydrogen will in turn enable developments including the use of low-carbon hydrogen as an energy source in industry.[255]

More efficient catalytic converters also reduce the costs of carbon sequestration and therefore enable new applications for industrial carbon capture and storage. This would make it possible directly to reduce carbon dioxide emissions in energy production, for example.

The potential afforded by quantum computing instead of traditional supercomputers in the energy-efficient performance of computationally demanding problems is also discussed in subsection 3.5.2.

Table 7: Possible climate and environmental impacts of quantum technology

Positive	Negative
• May have low energy consumption compared to supercomputers • Replacing carbon-intensive production processes with green solutions • Reducing the carbon dioxide emissions of coal power plants by using carbon sequestration • Reducing carbon dioxide emissions from transport through comprehensive traffic modelling	• Construction and administration of quantum computers, inclusive of materials • Consumption towards cooling • May slow down the phasing out of coal power plants

7.5 Augmented and virtual reality and media applications

Augmented reality (AR) refers to a view of the physical real-world environment superimposed with computer-generated information (e.g. image, sound, video, text, GPS data). Displays for viewing AR can be classified into three categories: head worn, handheld, and wearable and projective. Head worn display technology is further divided into two types. In optical displays, the user views reality through a see-through surface onto which the virtual information is superimposed. Video displays involve a video feed from a head worn camera that is then integrated with the virtual information before it is shown to the user on the display. Handheld displays may be devices such as smartphones. Augmented reality uses the device's camera to capture the video of the real world and combine it with virtual objects. Other wearable devices with

255 Boston Consulting Group, 2020. A Quantum Advantage in Fighting Climate Change.

displays, such as wrist worn devices with a display of sufficient size, are also comparable to handheld devices. Projection displays include portable video projectors that allow information to be projected on any surface.

In AR, the computer analyses the data obtained from various sensors, for example GPS location data, visual camera data and compass and accelerometer data, and uses it to combine the real-world view and the virtual elements as precisely as possible. The user can often also interact with the AR elements by touching a touchscreen, for example.

Virtual reality (VR) is an artificial environment created by sensations generated by means of computer simulation. VR seeks either to simulate the real-world environment or to create a wholly imaginary one. VR environments are typically based on a three-dimensional environment created on a screen. The environment can be generated as an immersive environment so as to allow the perception of actually being in the environment. In such a case, the screen is typically a special stereoscopic viewing device, i.e. virtual-reality glasses, or even a Cave Automatic Virtual Environment (CAVE) consisting of three of more projection surfaces creating an immersive environment in which the viewer can move about and also move the objects in the environment. Some simulation environments use further sensory stimuli such as simulated 3D sound or sensory motion stimuli.

VR may also refer to virtual worlds, which are computer simulations generated with two- or three-dimensional graphics. Users can create avatars – simulated, often anthropomorphic characters – to explore the virtual world. In multi-user virtual worlds, users actively interact with one another and shape their mutual experience of the virtual reality.

VR also covers applications where a user can view simulated panoramic images and control them by 360-degree horizontal rotation and also by (limited) vertical rotation. Likewise, virtual training environments and simulators that precisely simulate the operation of vehicles or machinery can also be considered VR.

AR and VR are associated with the wider concept of mixed reality, which can be seen as a sliding continuum from lightly augmented reality towards fuller immersion in virtual reality.

The development of AR and VR as well as the number of AR and VR applications has seen substantial growth in the past decades. The most important applications of these technologies have to do with communications, design, education and training, and entertainment.

The technologies relating to AR and VR are characterised by the same electronics typically being used for multiple applications, and the technologies can therefore have opposite impacts. While remote learning, for example, can deliver positive climate impacts, the VR electronics equipment can also be used for a vast volume of other services whose use calls for high computing power and much energy.

AR and VR applications are mostly used by private consumers and organisations. In terms of the field’s climate and environmental impacts, an essential question is whether e.g. VR technology will become a household staple – in other words, how high will the number of electronic devices relating to the technology rise. If the electronics were to become widespread among households, its applications should have significant positive climate and environmental impacts for the net impacts of the technology to remain clearly positive.

VR and AR can be leveraged for climate and environmental communications. Persuasive technology is a new field of technology designed to change the attitudes or behaviour of the users. VR allows the impacts of climate change to be communicated with increasing effectiveness, for example by enabling rising sea levels to be simulated for coastal dwellers.[256] AR could also be used to provide consumers with information on environmental impacts in support of their purchase decisions. AR can be utilised by showing consumers information relating to climate and environmental change on the various products and services in real time, when the purchase decision is being made. This could both enhance environmental awareness and facilitate the making of climate-friendly purchase decisions.

AR and VR may have a significant impact on design in all areas of society. The virtualisation of industrial manufacturing processes is one application that is already in use to some extent.[257] In practice, this means the full-scale testing, visualisation and product development of industrially manufactured products in a simulated environment. The application allows the design work to be performed globally and virtually among stakeholders, which reduces the need for the travel typically associated with product development and consequently the emissions of product development. Simulated prototypes can moreover wholly replace physical ones, which may reduce material use even quite significantly depending on the size of the prototypes.[258]

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[256] GeSI (Global e-sustainability initiative) & Deloitte 2019: Digital with Purpose - Delivering a SMARTer 2030.
[257] Ibid.
[258] Ibid.

To an increasing extent, digital reality is also being used as a tool in urban planning, design and development.[259] This has a clear positive impact on land use, as a better understanding already at the planning stage of the effects of the envisioned changes leads to better and more sustainable decisions on the placement of buildings and structures in a way that adapts to the existing environment. VR can also be leveraged for the needs of instruction and training (see also subsection 8.1.5). Like remote work and remote services, this reduces above all the negative climate and environmental impacts of travel.

Virtual travel allows the experience of travelling to different parts of the world to be provided virtually. Virtual travel can also enhance the actual experience of travelling and visiting new locations, for example by means of transporting the viewer from historical landscapes all the way to the simulated future. Many cities, Helsinki included, have announced their intent to provide virtual tourists with a travel experience that encourages traditional tourism. When this does not reduce tourism, its climate impact remains negative due to the high computing power required to build virtual worlds. If VR technology were to evolve to the point of hyperrealism and the computing capacity of the quantum computer could be harnessed to build virtual worlds, it might then be possible for virtual travel to become a genuine alternative to tourism and its climate impacts in the long term.

Table 8: Possible climate and environmental impacts of augmented and virtual reality systems

Positive	Negative
• Changes in climate and environmental awareness and in consumption habits • Reduction in material use and ancillary effects • A reduction in the need for travel reduces carbon dioxide emissions	• Virtual reality equipment use is highly energy consuming • Material requirements of electronics

7.6 Internet of Things (IoT) applications

The Internet of Things (IoT) refers to physical devices and objects connected to the internet. Wireless data transfer technologies relating to automation and digitalisation have seen intense development in the 2000s. Advances in wireless data transfer technologies in particular have contributed to IoT development. Several lighter technologies besides mobile networks and WiFi networks have also been developed

[259] GeSI (Global e-sustainability initiative) & Deloitte 2019: Digital with Purpose - Deliver-ing a SMARTer 2030.

to allow devices to communicate. The era of IoT may be deemed to have started at the turn of the millennium with technologies such as Bluetooth and RFID. While these early technologies solved short-range data transfer between devices, longer-range connectivity relied on other data transfer solutions. Technologies enabling the implementation of wider networks, such as NB-IoT, LoraWAN and Sigfox, have been developed in the 2010s to meet wireless IoT needs. Such technologies of long range and low energy consumption have enabled simpler and increasingly affordable end user devices with which to monitor, digitalise and automate a more and more diverse spectrum of real-life phenomena.

Advances in battery, sensor and radio technology and decline in the prices of the components used will allow an increasing number of devices to be connected to each other, various backend systems and the internet by means of wireless network connections. IoT applications allow the efficient collection of data and provide a better understanding of a given real-world process or phenomenon, and also permit the appropriate response to be made. This way, processes and various jobs can be made easier, faster and better by utilising and automating IoT solutions. In many cases, an application automated with an IoT solution also delivers positive environmental impacts, for example in the form of reduced energy consumption. The data collected by sensors and smart devices on their environment, themselves and their use is also viewed as an increasingly valuable resource. Device connection to one another, data collection and analysis, and possible remote control over a network connection enable the development of new kinds of smart and automated systems and digital entities.

Finnish telecommunications companies supply IoT and M2M connections for electrical and water meters, for example, but by leveraging their networks, various IoT end user devices and cloud services, they can also provide turnkey solutions for addressing challenges relating to energy consumption and resource efficiency in various processes in a wide range of fields of use. Turnkey IoT solutions generate positive climate and environmental impacts by reducing the need for mobility or vehicle use, among other things, which in turn reduces the climate impacts of fossil fuels.

A typical IoT application is location determination, which reduces the need to search for devices or materials, for example. The route for a vehicle can be optimised in advance when the application that plans the route is aware of the locations of things. On the other hand, IoT end devices can also collect data on processes or phenomena that used to be observed manually. Regular water levels in storm drains or the quantities of firewood present by the firepits in recreational areas, for example, can be checked by means of IoT-based data collection, reducing the need for on-site visits by vehicle. The real-time availability data on materials and components can also be improved with IoT solutions to avoid unplanned interruptions in production and to enhance responsiveness in the event of problems. Predictability enhances the efficiency and smooth flow of processes.

At present, the number of IoT devices is put at more or less 10 billion, depending somewhat on calculation method. The number of network-connected IoT devices is projected to rise at an annual rate of around 15% to reach 25 billion devices by 2025.[260] Current instances of IoT use range from simple water meter reading to transfer of real-time camera feed and machine analysis of video. In spring 2019, the most common network-connected device in Finnish households was the television (47%) followed by gaming console or sports device (24%).[261] Machine-to-Machine (M2M) SIM cards in IoT use numbered 1.6 million in Finland at the end of June 2019, an increase of 6% on the previous year.[262] Going forward, the number of automatic systems and applications based on data and analytics is set to rise even further.

IoT applications create the potential for entirely new products (e.g. smartbands) while also integrating into traditional devices such as televisions features that make use of information networks. This increases the demand for and volume of consumer electronics. The software of network-enabled devices may grow obsolete much faster than their physical components, which shortens product lifecycle and considerably adds to the amount of electronics waste. Even if the mechanical components of an IoT product were in prime condition, information security or the underlying network functionalities may have become outdated and prevent the use of the device altogether, or at least its information secure use.

IoT applications enable the optimisation of activities in a number of areas of use that are discussed in chapter 8. On the other hand, the applications also add to the amount of electronics, and issues relating to the lifecycle of electronics are discussed in chapter 5.

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[260] https://www.ericsson.com/4acd7e/assets/local/mobility-report/documents/2019/emr-november-2019.pdf

[261] Transport and Communications Agency Traficom: Consumer Survey of Communications Services. Published 29 May 2019. https://www.traficom.fi/fi/viestintapalvelujen-kuluttajatutkimus

[262] Transport and Communications Agency Traficom: Statistics on communications services. Updated 3 March 2020. https://www.traficom.fi/en/statistics-and-publications/statistics

Table 9: Possible climate and environmental impacts of –Internet of Things applications.

Positive	Negative
• Many IoT solutions enable the optimisation of other activities in numerous important areas of use and themselves have low energy consumption	• In consumer use in particular, IoT solutions may add to the number of devices and shorten their lifecycles, thus generating electronic waste

8 ICT sector as a provider of climate and environmental benefits

Information and communications technology (ICT) is an integral part of modern society and it is used to provide services to businesses, public administration and individuals alike. Around 70% of the world's population use ICT, and it has been submitted that the emissions generated by the sector should be prorated with the number of people making use of ICT solutions. The sector's per-capita emissions are low compared to many other sectors, for example aviation or road vehicles.[263]

Of particular interest from the perspective of this report are the benefits that ICT can deliver to the efforts to stop the progression of climate change and environmental degradation. Traditionally, growth in GDP has increased carbon dioxide emissions. Digitalisation is seen as an opportunity to combine GDP growth with a reduction in total carbon dioxide emissions when goods are replaced with services or mobility emissions decline thanks to remote access.

According to the low-carbon roadmap commissioned from AFRY by Technology Industries Finland (version of 15 May 2020), the handprint of the ICT sector is considerable and the potential of the ICT cluster in reducing climate emissions is estimated to be at least 5 Mt carbon dioxide equivalents annually.[264] The solutions generated by the sector also play a central role as enablers of emission reductions in other sectors and industries. Key technologies in this respect include telecommunications solutions, cybersecurity and local solutions that integrate the Internet of Things (IoT) and sensor technology.

When looking to ICT for a solution to the problems arising from climate change or environmental degradation, it should be noted that ICT technology alone and in and of itself is not the answer – what is crucial is how and where technology is utilised and what effects this will have on the traditional ways of doing things that cause climate change and lead to overconsumption of natural resources.

It is estimated that over the next ten years, around EUR 3 trillion will be spent globally on ICT sector research and product development.[265] In developing new solutions and services, it is important to pay particular attention to their climate and environmental

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[263] Ericsson 2020: A quick guide to your digital carbon footprint.
[264] The sector's own footprint has been excluded from this estimate.
[265] https://gesi.org/storage/files/DIGITAL%20WITH%20PURPOSE_Summary_A4-WEB_watermark.pdf

impacts so that the introduction of the technologies supports the shared goals of mitigating climate change and reducing emissions.

ICT technologies have the potential to bring people, machines, equipment and objects together while facilitating communication and to provide an opportunity to monitor trends in our environment and its state. We can also analyse the impacts of different actions and then correct and optimise our activities based on the data collected. Current practices that are environmentally damaging can be made cleaner and less damaging by utilising data collected and forecasts generated with various digital tools. With regard to optimising activities and increasing their efficiency, a rise in the degree of automation also delivers new benefits to the functioning of processes and systems.

The following sections describe some of the potential climate and environmental benefits obtainable through ICT solutions in various sectors and domains.

8.1 ICT as an enabler of the carbon neutral and resource efficient society

The United Nations has determined 17 Sustainable Development Goals (SDGs) to be achieved by 2030.[266] These goals address our global challenges and provide the blueprint to achieve a better and more sustainable future. Some of the SDGs relate to tackling climate change, reducing environmental pollution and preserving biodiversity while others relate to promoting the equal economic opportunities and social equality of people. All of the SDGs are also inter-connected.

Going forward, technological advances and the successful utilisation of ICT technologies is perceived to play a major role in the achievement of many of the goals adopted. Digital technologies can assist in the efforts of many sectors towards energy efficiency, carbon neutrality, process waste minimisation, material consumption reduction and circular economy promotion. Together, the different sectors can contribute to the achievement of the SDGs. Attention must nonetheless be paid to the proper use of technology so as to avoid it leading to the opposite result. The correct incentives, shared policies and investment into creating a better understanding of new digital approaches can steer development in a positive direction.

[266] https://www.un.org/sustainabledevelopment/sustainable-development-goals/

8.1.1 Smart cities and housing

In the future, an increasing number of the world population will live in cities of various sizes. The world's cities are responsible for up to 70% of the world's greenhouse gas emissions.[267] Going forward, the functions and services of sustainably developing smart cities will require an increasingly diverse communication network as well as smart traditional infrastructure that leverages ICT.

In the cities of the future, data collected with devices linked to the digital infrastructure and sensors making use of the Internet of Things (IoT) can be used to form a real-time picture of the functioning of the city, which may in turn be utilised to steer the city's functions in a direction that is more efficient, environmentally friendlier and better serves residents' needs. Data collected on the smart city's infrastructure and functionalities and the conclusions drawn from such data can help cities better manage their resources and provide city residents with increasingly effective services to improve the entire city's functioning as well as the smooth running and convenience of its residents' daily life.

Based on the data collected, the city's various functions can be monitored and also modelled to identify the optimal approach. ICT solutions can be used to improve the energy efficiency of city functions, more effectively respond to people's mobility needs, optimise the utility networks for electricity, heat, domestic water and wastewater, improve safety and security in the city and innovate new services.

The public transport system, for example, can be optimised to changing conditions and its climate impacts reduced while also enhancing the customer experience. Public transport fleet management can be partly automated to make public transport more efficient. Utilising real-time traffic and conditions data generated by various backend systems and network-connected cameras and sensors can allow the provision of reliable and precise route information, which in turn makes mobility efficient and transfer times more accurately predictable.

In the future, public transport in smart cities will also to an increasing extent make use of connected, automated vehicles that utilise new technologies. The efficiency and effectiveness of public transport, the predictability of the time spent en route and the rising prevalence of mobility services drawing on new kinds of digital platforms are expected to contribute to a decline in the need for private cars and an ensuing reduction in the greenhouse gas emissions arising from traffic. New kinds of incentive schemes could be implemented with the help of mobility data and artificial intelligence

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[267] https://mirror.unhabitat.org/downloads/docs/E_Hot_Cities.pdf

(AI). For example, when AI observes that an individual favours public transport over travel by private car, the individual could accumulate tokens for use in public services, such as paying for sports facilities usage.

Smart cities will require increasingly advanced smart networks for the distribution of utilities such as electricity, heat and water. An important trend in the power system is the rapid increase in variable renewable electricity, such as wind and solar power. The integration of this new weather-dependent production into the power system and the electricity market will require digital solutions to develop new supply- and demand-side flexibility approaches. Digitalisation will enable demand-side flexibility by enabling the automated smart metering of electricity and heat consumption and the responsiveness of the various energy systems to metering data and dynamic pricing.

Actual and projected energy consumption data as well as data on energy prices can be utilised in conjunction with systems such as building automation, electric vehicle charging, process control and district heating production technologies to increase flexibility in energy demand. In the electricity system, smart meters are already commonplace in Finland. While demand-side flexibility has been a fact of life in large-scale industry for quite some time, development is still in its initial stages in respect of small-scale industry, homes and the electric vehicle charging infrastructure.

Besides electricity, also the distribution of water and heat will benefit from digitalisation developments. Sensors and high-performance networks can be used to introduce increased remote control in facilities. Network leaks need to be identified in an efficient and timely manner and responded to quickly with maintenance. The quality and consumption of domestic water, for example, can be monitored in real time, and the causes of any irregularities can be efficiently determined and pinpointed. Remote metering in district heating has already become the norm.

Smart buildings utilise digital solutions to allow them to adapt to the prevailing conditions and usage needs. ICT solutions can help improve energy efficiency by means such as adjusting the heating, air conditioning and lighting of premises according to usage needs and reducing these when the premises are unoccupied. Energy saving with automation is a key IoT application area. Today, building unit-specific temperature readings can be cost-effectively obtained by means of wireless temperature sensors. Once the heating control system is aware of the temperature in the building units, heating can be optimised to reduce unnecessary heating.

It has been estimated that in apartment buildings, for example, unit-specific temperature monitoring data can achieve energy savings of up to 10%, which is equal to around one month less of the heating season.[268] Smart buildings can automatically optimise their functions on the basis of historical data collected from sensors, machine learning and the use of the premises as well as forecasts based on these and conditions data. Efficient utilisation of building surfaces for e.g. solar power production can allow smart buildings to act also as sources of renewable energy, and the energy can also be stored in local energy storage facilities.

Software used already at the building design and construction planning stage can enable greenhouse gas-minimising choices for the building's entire lifecycle. Globally, the built environment is responsible for around 30% of greenhouse gas emissions, 40% of primary energy consumption and 50% of raw material consumption.[269] Consequently, such choices can deliver considerable benefits.

Going forward, the rise in the global population and their purchasing power will heighten product consumption and the associated consumption of various materials. Global materials consumption is projected to more than double from 2011 to 2060.[270] Technological advances and product lifecycle planning helps make the use of materials more efficient and to avoid a situation where the need to produce materials would increase in step with the increase in the quantity of products. The recovery of current materials and the efficient implementation of the circular economy requires the introduction of ICT solutions at various phases of the process. By leveraging technologies such as IoT, machine learning and blockchains, the current resources can be kept in maximally effective use while at the same time extending the service life of resources. Intelligent assets enable the location, condition and availability of goods to be tracked. In addition, digital ownership and trading of goods along with automated contracts open up an opportunity to develop new services and to utilise goods efficiently and improve resource efficiency.[271]

Using AI, cities can also implement intelligent traffic control systems. Intelligent traffic control refers to the utilisation of smart sensors and measuring devices to improve traffic flows in major cities in particular. One example of applying AI to traffic control comes from Moscow, where utilisation of the technology has reduced traffic congestion and halved search times for available parking spaces in the city.[272] The application directly reduces emissions from traffic by shortening travel times and

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[268] https://www.helen.fi/en/housing-companies/heating-for-housing-companies/energy-efficient-heating-in-a-housing-company
[269] Ministry of the Environment.
[270] https://www.oecd.org/environment/waste/highlights-global-material-resources-outlook-to-2060.pdf
[271] Ellen MacArthur Foundation 2016: Intelligent Assets: unlocking the circular economy potential.
[272] International Telecommunication Union (ITU) 2020: Frontier technologies to protect the environment and tackle climate change.

reducing vehicle idling and travel volumes, and it has a positive impact on local air quality.

8.1.2 Intelligent transport

In the future, the development of collaborative, connected and increasingly automated means of transport and digitalised systems will contribute to reducing environmentally harmful emissions originating in passenger and goods transport. Automation and the utilisation of information can, among other things, optimise routes and capacities and in that way help reduce environmentally harmful emissions from transport. Automation in and of itself generally does not accomplish the positive emission impacts. Instead, emission reductions arise from the changes in means of transport, their functioning and control – and consequently in the entire transport system – that take place as a result of automation.

Road

In road transport, connected vehicles and intelligent transport systems will to an increasing extent rely on various kinds of ICT in the future. These solutions will allow the development of transport towards greater smoothness, safety and environmental friendliness. To date, the main driver in transport automation development has been to increase efficiency and to advance road safety and mobility services, yet more and more attention is now being paid to emission impacts.

A key driver of the development of automated vehicles is vehicle connectivity, i.e. vehicles communicating directly with one another, the road transport infrastructure, various backend systems, and the overall environment. The different parts of the road transport infrastructure can also communicate with each other. This results in a connected and interlinked entity that can be leveraged to improve the efficiency and safety of mobility and transport. Connected vehicles can communicate their own movements and their observations of road conditions, such as weather, congestion, emergency braking situations or slippery patches of road, to other road users and also be warned about potential hazards, such as accidents or closed lanes. Gaining more information and sharing it helps make traffic smoother and more efficient and can therefore also help reduce emissions.

Automated vehicles are divided into five different levels of autonomy, and high-level automation applications are being developed for both privately owned vehicles and public transport fleets. At the level of transport system, the scope of the changes depends on the degree of automation in transport. Different estimates on the development of automation have been put forward in Finland.[273] Over the next ten years, automation in road transport will be of little significance at the transport system level, since only around 1.2–3.5% of the vehicle stock would support highway autopilot driving and automated transport vehicles would account for 0.4–2.8% of the vehicle stock.[274] The magnitude of the impacts also depends on whether the automated functions of vehicles are informative, recommendatory or peremptory.

In respect of road transport automation, its environmental impacts can also serve to increase emissions if it results in increases in kilometres driven or a shift in modal distribution away from low-emission modes of transport. The sub-measures presented below can likely reduce emissions also in Finland.

Firstly, the automation of vehicle technology and operation can reduce the energy consumption and emissions of vehicles by means including more efficient driving style and 'eco-driving'. This involves programming the vehicle to avoid unnecessary acceleration and braking. The optimal driving speed in terms of emissions can also be adapted to prevailing conditions. At the same time, the risk of accidents can be reduced, and when the number of accidents falls as a consequence, emissions will also fall when the congestion caused by accidents decreases.

Secondly, positive environmental impacts can also be achieved by increasing communication between vehicles themselves, between vehicles and infrastructure, and between vehicles and devices. These can be used to reduce emissions by means such as connected platoons of trucks driving closely together under the guidance of communication links, resulting in benefits such as reducing the impact of air resistance on fuel consumption. Connected vehicles can also communicate with each other and transmit condition reports to allow individual vehicles to select optimum speed and to optimise traffic flow as a whole.

Thirdly, integrating road transport automation and connectivity into the existing public transport system can deliver a sustainable change in mobility, which will reduce emissions originating in the transport system. Feeder traffic to key public transport corridors, for example, could be provided by automated or remotely controlled minibuses and robot taxis. The future will also see progress in car sharing and ride

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[273] EU-EIP, Activity 4.2. and Ministry of Transport and Communications: legislative and action plans for transport automation

[274] https://www.traficom.fi/sites/default/files/media/publication/EU_EIP_Impact_of_Automated_Transport_Finland_Traficom_6_2019.pdf

sharing services of various kinds. Used alongside public transport, these can provide reductions in total emissions.[275,276,277]

Solutions will also be needed to address the charging infrastructure of electric vehicles as electrification spreads in road transport. Smart systems can create demand-side flexibility and stores of electricity, which reduces in particular the need for peak power from fossil fuels.

Rail

The potential of rail traffic in emission reduction is realised above all through a rise in the market share of rail transport and in the capacity required for such transport. Digitalisation enables increased automation on railways, from which improved efficiency, punctuality and capacity follow. An improved and more punctual rail service offering supports the transition to environmentally sustainable modes of transport, enhances the attractiveness of railways and boosts the market share of rail transport.

In Finland, rail transport is currently estimated to account for only around 1% of greenhouse gas emissions from transport, as the railway network in Finland has largely been electrified and trains for the most part run on renewable electricity. A higher market share for rail transport would significantly reduce transport emissions. At present, rail transport accounts for around 6% of all passenger transport and around 27% of all goods transport. Increasing the share of rail transport is an EU-wide goal that has a strong presence in agendas including the European Green Deal.

The transition to climate neutrality calls for smart infrastructure. Digitalisation and the increased efficiency that it enables could add as much as 30% more capacity to railways.[278] In Finland, the Digirail project has studied ways for using rail capacity more effectively. With digitalisation, service frequency and therefore also the capacity of the rail network could be increased. This would reduce bottlenecks in the rail network, speed up recovery from disruptions, facilitate timetable planning and improve punctuality, which in turn enhances railway attractiveness and performance.

In future, railway digitalisation will enable a higher degree of rail transport automation to Grade of Automation (GoA) levels 1–4. At GoA level 1, the train driver controls the

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[275] Makridis et al. 2020: The impact of automation and connectivity on traffic flow and CO_2 emissions. A detailed microsimulation study. Atmospheric Environment.
[276] Stogios et al. 2019: Simulating impacts of automated driving behavior and traffic conditions on vehicle emissions. Transportation Research Part D.
[277] Wadud et al. 2016: Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles. Transportation Research Part A.
[278] https://digirata.fi

train with the automatic train protection system in operation. At GoA level 2, starting and stopping are automated, but the driver initiates automatic driving and can operate the doors and monitors the running of the train. At GoA level 3, starting and stopping are fully automated but staff is present in case of emergencies. At GoA level 4, the train is fully automated without any on-train staff even to attend to emergencies. As the degree of automation rises, the above-mentioned benefits can further be boosted.

Sea

Automation solutions are already in use in maritime transport for purposes such as optimising navigation and trim. As the degree of automation rises going forward, the ship operator may be on land and control more than one ship at a time. At the same time, more advanced solutions are estimated to enable developments such as the more effective integration of shipping into the overall system of logistics, which would reduce fuel consumption and consequently also emissions. Further into the future, the autonomous operation of ships would largely eliminate the role of operator, and ships instead would run wholly independently.

Air

Aviation automation is an element of unmanned aviation that is set to increase strongly with the advent of e.g. drones. Drones can be used for purposes such as last-mile deliveries to shift package deliveries away from vehicles on congested roads to less congested aerial delivery. This has already been piloted in Finland as well. It is foreseeable that unmanned aviation will in future expand to encompass also the transport of freight and passengers, but this will take time and require a great deal of further development effort. Going forward, positive climate and environmental impacts can be achieved through automated air traffic control utilising ICT technologies and also with the free optimisation of flight routes in busy areas.

Section 9.1 addresses in more detail the ICT-derived potential and solutions for minimising climate and environmental impacts in the logistics sector.

8.1.3 Digital transformation in industry

Using digitalisation to improve the operational efficiency of industry is being referred to as the Fourth Industrial Revolution or Industry 4.0. This ongoing transformation will continue throughout the current decade. The increase in the degree of automation in industry accomplished with ICT solutions will improve the energy and materials efficiency of operations and occupational health and safety and also enhance the efficiency of production processes and supply chains while boosting the competitiveness of industrial activities. Elements central to this transformation are the application of efficient wireless technologies such as 5G, industrial IoT and machine learning, efficient data utilisation, and enhancement of human-machine interaction in areas such as industrial production process optimisation, efficient resource utilisation, quality enhancement and wastage minimisation.[279]

Advances in technology have already outlined a path from technology-enhanced industry (Industry 4.0) through flexible and sustainable industry enabled by human/machine interaction and collaboration (Industry 5.0) all the way to strong, antifragile industry (Industry 6.0).[280] The Fourth Industrial Revolution integrates systems and creates decision-making based on analytics, while in the Fifth Industrial Revolution, the role of machine learning increases with the aim of ever closer human/machine interaction that enables increasingly environmentally friendly modes of production and industrial regeneration. The Sixth Industrial Revolution envisions production as an increasingly personalised ‘service’ that caters for sustainability more widely than ever, and not solely from the environmental perspective.

Remote assistance and advisory solutions implemented by means of new technologies such as AI and augmented reality can in future assist e.g. maintenance and installation workers by increasing the efficiency and safety of job performance. This will allow the assembly of various machines and equipment, for example, to be carried out in a way that may even fully eliminate the possibility of human error, or at the very least reduce it significantly. Automation moreover enhances the safety of job performance, as it reduces the number of industrial accidents and lessens exposure to occupational diseases. AI can also be employed to optimise the routes taken by robots, machinery and people in factories, which will improve safety and efficiency.

Troubleshooting can be accomplished without extended assembly shutdown periods by using data collected from the production process and solutions that enable the telepresence of experts. As a result, the customer returns of the products manufactured can be minimised, which reduces product transport as well as greenhouse gas emissions. Damage and equipment failure caused by products of sub-standard quality can also be reduced, which promotes overall efficiency and reduces the unnecessary energy consumption generated by these.

One example of the benefits achievable with ICT solutions comes from the pulp production control and automation system developed by VTT Technical Research Centre of Finland in collaboration with the forest industry and an automation

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279 Stock & Seliger 2016: Opportunities of Sustainable Manufacturing in Industry 4.0. Procedia CIRP.

280 Allied ICT Finland 2020: Whitepaper by Allied ICT Finland - From Industry X to Industry 6.0 – Antifragile Manufacturing for People, Planet, and Profit with Passion (draft).

company. Based on measurement data and AI, this system allows the same amount of pulp to be produced from a significantly lower amount of raw wood. The reduction in raw wood for a single pulp mill is around 700 truckloads, which is equivalent to 2–3% of total annual raw wood consumption. The automation system consumes the same amount of electricity as earlier-generation systems. The mechanism of climate impact from reduced consumption of wood is threefold: the carbon stored in trees remains in the forest, the eliminated 700 truckloads generate no emissions, and lower raw material consumption reduces emissions at the mill.[281]

Another example of improvement through ICT comes from the electric vehicle battery pack manufacture solution implemented by telecommunications company Elisa. The challenge came from inconsistent production quality and high scrap rate, as well as the trial-and-error based approach to enhancing efficiency. The new ICT solution involved the integration of Operational Technology (OT) environment in the production data lake, followed by a demonstration, through predictable quality analysis, of the data models that in actual fact impacted on battery pack quality. The solution implemented reduced the process scrap rate by 15–19%.[282]

Another industry technology seen to play a significant role is Additive Manufacturing (AM), also referred to as 3D printing. These are technologies that allow the on-site production of components on the basis of a digital template. Great advances in the technologies have been seen in recent years. The number of printable materials and components as well as products has risen and the technologies are being used in an increasing number of applications. Printing from digitally optimised templates with advanced materials allows components to be made lighter and more durable than with traditional manufacturing methods. Materials made from renewable raw materials are also being introduced to an increasing extent.

Going forward, these technologies are believed to complement and perhaps even to replace current manufacturing methods and consequently to transform manufacture towards greater environmental sustainability. 3D printing supports the circular economy through the flexible production of spare parts for products, machinery and equipment and also through the longer useful lives made possible by new and advanced materials. In AM, raw materials can be quite efficiently utilised in the manufacturing process compared to techniques that remove or shape materials (milling or casting, for example) where material loss may be quite high relative to the finished product. In addition, printing technologies allow a large portion of surplus

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[281] Saarela & Poukka 2017: On-Line Pulp Quality Information. Automaatiopäivät 22 [Automation Days 22].
[282] https://www.elisasmartfactory.com/case-study-battery-production/

materials to be reused and currently, up to 80% of the surplus can be reused in the following production batch.[283]

8.1.4 Solutions in the natural resources sector

Agriculture that makes extensive use of ICT solutions (‘smart farming’) can generate an accurate situational picture and respond to changes in a timely and appropriate manner. Smart farming solutions are also relevant to increasing agricultural productivity and adapting to climate change. For example, when earlier the exact same treatment was applied to an entire field, smart systems allow the necessary measures to be targeted to precisely the right place at the right time. This can be accomplished by means of data generated by sensors and imaging and the situational picture generated from this data. Data collection can make use of various kinds of connected sensors that allow data on growing sites to be combined with footage obtained by e.g. drones or satellite. All together, these can digitally formulate a situational picture of the prevailing status, possible lack of nutrients or water, plant diseases, soil and growing conditions and any action required on the basis of these.

Local soil and growing conditions data as well as weather forecast data can be precisely taken into account when planning steps such as irrigation and the use of fertilisers and pesticides. Looking further into the future, action could even be taken automatically by means of drones or other autonomous machines. This way, production processes can be made more efficient and better information can be obtained on the effects of action taken while at the same time avoiding any needless harmful environmental impacts. As a result, the unnecessary operation of machinery and the surface erosion caused by machinery can be avoided, along with the greenhouse gas and particulate emissions generated by machinery operation. Preventing loss of carbon from fields by keeping the soil covered with vegetation and maintaining or increasing soil carbon content are tools currently being investigated to prevent greenhouse gas emissions from agricultural land. The growing prevalence of biogas production from manure also helps reduce greenhouse gas emissions in the agricultural sector. Technology plays a key role in determining and reducing climate and environmental impacts.

Going forward, ICT solutions will deliver benefits in the field of forestry through increased automation and higher efficiency in activities such as forest status and growth monitoring, efficient forest management, storm damage monitoring and pest control. Various kinds of satellite or drone-based imaging solutions allow information to be obtained on the status of forests and the size of their biomass, from which the

[283] https://www8.hp.com/uk/en/printers/3d-printers/materials.html

forest's carbon sink activity can be calculated. Imaging also enables less vehicle-based monitoring. Consequently, the emissions from vehicles are reduced and damage to soil surfaces caused by vehicles can also be avoided to some extent. Imaging can also efficiently collect data on wildfires and guide extinguishing to a prompt schedule – reducing the amount of carbon dioxide released by fires into the atmosphere.

According to the report on emissions in the agricultural and forestry sector[284] published by the Government of Finland in February 2019, carbon sinks play a vital role when examining the potential of the land use, land-use change and forestry (LULUCF) sector to further the achievement of Finland's climate goals. Digital solutions can facilitate forest management that boosts carbon sinks.

8.1.5 Public services

The aims of digitalising healthcare include increasing the overall efficiency of healthcare, achieving cost savings and enhancing access to care and treatment irrespective of location. These aims could be achieved with the help of e.g. healthcare provision assisted by virtual channels and solutions and telemedicine solutions that efficiently leverage telecommunications connections. ICT solutions also provide benefits in the areas of health promotion and disease prevention by utilising telemonitoring and remote monitoring.

The increasing prevalence of various end user devices such as smartphones has made health monitoring easier and, with advances in the technology, also more accurate. As it has become easier to monitor one's own health and activity, growing importance is being attached to investment in personal health. Proactive healthcare that leverages data and technology seeks to promote health and address health issues before they even arise. In this context, ICT solutions play an identifiable role.

Developments in sensors and the expansion of high-performance telecommunications networks have enhanced the potential for telemedicine and telemonitoring. Patients can share the data collected by sensors with their doctor online and after analysing the data, the doctor can update the patient's treatment plan without the patient having to make an appointment and travel to visit the doctor's office in person at a specific time. This reduces the need for mobility, which presents a further benefit for patients who find it difficult to get about. Going forward, medicines and other medical supplies

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[284] Aakkula et al., 2019: Maatalous- ja LULUCF-sektorien päästö ja nielukehitys vuoteen 2050 [Development of emissions and sinks in the agricultural and LULUCF sectors until 2050]. Government´s analysis, assessment and research activities.

could also be delivered efficiently and in a timely manner by means such as drones.[285]

Digitalisation has already introduced and will continue to bring about an increasing number of changes to education and training. Distance learning has grown more and more effective thanks to the rising prevalence of learning materials and virtual instruction available online. The video recording of lectures to allow them to be accessed irrespective of time and place has reduced the need for mobility. Virtual reality applications can be developed to enable practical exercises that allow students effectively to learn and perform procedures correctly and efficiently in simulated conditions. The consultation and guidance provided by teaching staff can also be arranged digitally over a network connection when necessary. Education provision to an increasing extent on digital platforms will in future also affect urban planning and public transport planning, should there be less need to physically access centralised campuses and schools.

ICT-based public online transaction services can also enhance the efficiency of the administration of various schemes aiming to reduce emissions, for example the online transaction services, based on multi-level ICT solutions, provided by the Energy Authority in the Finnish Emissions Trading System (FINETS) and the renewable energy subsidy scheme. The FINETS online transaction service is believed to have promoted the consistent monitoring of emissions on the basis of a common set of ground rules and to have improved the credibility of emissions information between the trading participants. The subsidy service, meanwhile, has enabled the administration of subsidy decisions, including verification of electricity production monitoring system and measurement compliance.

8.1.6 Consumer services

The digital transformation is also present in consumer services. With digitalisation, physical products are to some extent replaced by virtual products and digital services, which may serve to reduce material and energy consumption. Aspects examined in the report by Ericsson[286] include the extent to which online streaming services have superseded traditional CDs, DVDs and Blu-ray discs. The report estimates that streaming a two-hour movie and watching it on a laptop computer consumes less energy than watching the same movie on a television from a traditional DVD or Blu-ray disc (see also section 2.3). In today’s homes, well equipped with internet access, video can be transmitted to any number of end user devices. The energy efficiency of

[285] Subbarao & Cooper Jr 2015: Drone-Based Telemedicine: A Brave but Necessary New World. The Journal of the American Osteopathic Association.
[286] Ericsson 2020: A quick guide to your digital carbon footprint.

televisions has improved over the years, although screen sizes have also increased at the same time. As a result, the energy consumption of televisions has remained fairly unchanged. The greatest impact is generated by the manufacture of physical discs and their transport and distribution, which all require energy and all of which generate emissions. Similar developments towards digital services and away from physical products have also been seen in the field of music.

The future solutions in the media and entertainment industry relate to the production and distribution of increasingly compelling content. This development centres on the provision of entertainment experiences by means including better-quality video as well as augmented and virtual reality solutions. Going forward, more and more content will be produced in High Definition (HD) and 4K and 8K resolution. 360-degree camera technology and parallel video streams offering viewers different camera angles to choose from will be utilised to an increasing extent in the future. Various kinds of data will also be integrated on top of this; for sports events, for example, information to illustrate capability and performance could be provided on the athletes and the individual events. These allow viewers to consume media and entertainment services in an increasingly comprehensive manner, and also with the option of service tailoring. Increasingly high resolution translates into a growing need for processing and data transmission capacity. Multiple different parallel video streams also add to the total volume of transmitted data. New kinds of entertainment services may consequently also increase the energy demand of networks and end user devices.

ICT can enable a significant reduction in the need for mobility in respect of daily commuting and also longer business trips. Replacing work-related travel with virtual meetings and teleconferencing reduces the need for travel. Especially long-distance travel, which typically requires flying, causes significant carbon emissions when frequently undertaken. Telecommunications company Elisa has studied the impact of remote work and time and location independent work on emission reductions. The report concludes that virtual meetings can deliver an average emission reduction of 3.85 kg CO_2 per day of remote work. Correspondingly, it has been estimated that avoiding travel and making use of virtual meeting services would deliver an average emission reduction of 2.49 kg CO_2 per person taking part.[287]

From the viewpoint of consumption, ICT enables direct emission and materials reductions when a more polluting and resource-intensive function is replaced with a virtualised service. However, the total impact and development over the longer term is determined by the extent of change in behaviour at the level of society – how widely we embrace new ways of doing things, how fully they replace older ways, and what

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https://corporate.elisa.com/attachment/content/Elisa-Energy-and-CO2--emission-disclosure-2019.pdf kinds of new consumption models these new ways possibly create. It has been proposed, for example, that the emission reductions achieved through wider remote working could in part be cancelled out by a corresponding increase in leisure travel. Likewise, impacts across the entire lifecycle should be better understood when examining climate and environmental impacts of the media and entertainment industry, taking into account also changes in consumer behaviour such as a possible significant increase in media content consumption.

Several consumer applications that allow people to learn about the emission impacts of their own consumption are also currently available and under development. Easy-to-use tools help consumers interested in complex environmental issues to perceive the scale of issues and monitor the impacts of their own actions. For the time being, any estimates of the effectiveness of these new tools in cutting emissions would be premature.

8.2 Climate and environmental research and climate change adaptation

8.2.1 ICT in support of climate change adaptation

Even if good progress were to be achieved in climate change mitigation, global warming cannot be fully prevented. Rapid changes in temperature and water conditions affect the natural environment and human societies, and this calls for preparedness and adaptation. ICT can support this vital adaptation in many different ways. ICT not only facilitates climate research (see also subsection 8.2.2) and helps improve weather forecasts that are essential for preparedness but also provides very concrete risk-reducing solutions.

The most immediate population-related risks are faced in populous coastal states and small island nations due to rising sea levels as well as in regions already suffering from drought, such as Sub-Saharan Africa. The number of people exposed to extreme heat is also increasing.[288]

Remote sensing, geographic information systems and risk assessments based on these play an increasing role in preparedness for extreme weather phenomena in countries like Finland, too. For example, the forest fire warning system is designed to inform the general public and fire authorities about the risk of wildfires caused by dry

[288] https://www.bbc.com/news/science-environment-52543589

terrain, with the risk assessment based not only on weather observations and forecasts made by the Finnish Meteorological Institute but also on a drought evaluation index concerning terrain flammability. As well as helping to obtain the data employed (weather stations, satellite observations) and produce more accurate models, ICT also helps communicate the results effectively.

Risk warning and advisory systems based on mobile applications are among the tools provided by ICT for preparedness. However, this calls for well-functioning networks and people's access to devices – something that cannot be taken for granted on the global scale. A variety of systems of mobile phone networks and mobile weather stations have been developed in response to these challenges.[289]

In addition to preparedness for immediate risks to life, ICT also provides slightly longer-term solutions for issues such as agricultural adaptation. For example, soil monitoring can be used to facilitate irrigation planning. ICT applications based on positioning can help monitor the status of freshwater reserves that are vital for agriculture and other societal functions.

8.2.2 ICT and environmental research

Just like in other disciplines, the benefits of ICT in environmental research and climate science are obvious. ICT is utilised across the board from data collection, storage and processing as well as modelling to data sharing and communication to the general public. Knowledge-based decision-making must be backed up by the best possible reliable information that can be verified through openness and peer review.[290]

ICT increases the efficiency of research data collection at facilities such as automated measuring stations that can be used to measure and monitor the temperature of air or water or the concentration of various substances including contaminants in air or water. Citizens' observations can provide supplementary data for research. ICT and various tailored applications, such as the mobile phone application of the Lake & Sea Wiki of the Finnish Environment Institute SYKE, support the submission, recording and processing of such observations. Easier storage of big data, various search functions and improved modelling thanks to increased computing power are also examples of the advantages of ICT in the various stages of the research process.

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[289] https://www.wri.org/our-work/project/world-resources-report/icts-key-technology-help-countries-adapt-effects-climate
[290] The need to improve access to public information is supported by EU Directive 2019/1024 on open data and the re-use of public sector information.

Data visualisation and communication channels for the general public have also improved considerably because of ICT.

Advanced ICT solutions and compelling digital visualisations of biodiversity also enable a new kind of environmental communication. Through increased awareness, this may affect consumer behaviour and be positively reflected in environmental and climate change. One study indicates that 88% of those who watched the episode of the BBC series *Blue Planet II* on plastic altered their consumer behaviour as a result.[291] Drones were used extensively to provide the footage for the series.

8.2.3 Examples of ICT in biodiversity research and conservation

This report has focused especially on the benefits of the ICT sector in action against climate change and on the ICT sector's own climate emissions. Biodiversity loss is a serious trend threatening humanity's wellbeing that stands right alongside climate change in terms of its gravity. A few examples of the benefits of ICT in biodiversity research and conservation are provided below. These examples are only a snippet of what is available but help illustrate the cross-cutting significance of ICT.

Habitats, their loss or successful protection as well as individual occurrences of species can be mapped and monitored using remote sensing methods. Methods of data analysis that have evolved thanks to ICT also facilitate the processing of biodiversity data. Combining satellite observations, DNA sequencing and advanced ecological modelling can help gain deeper insights into data obtained with a single observation method.[292]

In recent years, progress has been made in the mapping of species that are difficult to survey, such as bird species of Brazilian rainforests or fungal and bird species elsewhere, by using sound sampling and partially automated equipment. Species knowledge is key to our understanding of ecosystem function, but the number of species that have yet to be described is so enormous (up to 80% extant species on Earth) that they could never be discovered using traditional methods. The LIFEPLAN – A Planetary Inventory of Life project led by the University of Helsinki uses semi-automated sampling methods to collect global biodiversity data and uses the data to produce distribution models projecting the future.

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[291] Waitrose & Partners Food and Drink Report 2018–2019.
[292] https://www.nature.com/articles/s41559-017-0176?proof=true

Natural history museums play an important role as regards the storage, use and sharing of data on species and their diversity. Digitisation of collections serves research and monitoring as well as nature enthusiasts and the general public. The accessibility and usability of data is improved internationally through various joint projects and agreements between museums.

Not only is communicating research findings and sharing museum collections more efficient thanks to ICT, but various ICT applications can be used to provide biodiversity information and increase people's interest in biodiversity preservation. Recent years have seen high popularity for webcams set up by civil society organisations that allow people to watch, for example, the endangered Saimaa ringed seal sunbathing on a rock by the lake or a rare bird of prey nesting successfully. There are also applications that use AI to reliably facilitate species identification by nature enthusiasts and can also be used to collect citizens' observations for research.[293]

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[293] www.inaturalist.com

9 Case examples of ICT as an enabler of greenhouse gas emission reductions

The following presents a more in-depth analysis of two extensive cases where the efficient utilisation of ICT solutions can generate positive climate and environmental impacts.

9.1 Logistics

Nearly 90% of the tonnage in Finland's domestic goods transport is transported by road. When comparing the shares of the modes of transport in tonne-kilometre (i.e. the transport of one tonne of goods over the distance of one kilometre, tkm), the differences even out to some extent, yet road transport still accounts for around 65% of total transport performance with rail transport accounting for around 28% and transport by waterways for 7%.[294] The vast majority of exports and imports in foreign trade is transported by sea. [295] In 2018, trucks operated transport journeys totalling 1.9 billion kilometres in length[296] and the loading rate was 71%.[297]The figure includes transports of empty containers, pallets, roller cages and the like but excludes empty runs. When empty runs and the transport of empty containers, etc. are taken into account, the capacity utilisation rate in goods transport in Finland comes to around 57%.

The volume of goods transported depends on the quantity of goods headed for consumption. The total number of tonne-kilometre in Finland has increased since 2014 but changes in the industrial production structure have been estimated to reverse this growth into a slight decline after 2040. However, the share of domestic road transport in the estimates remains high.[298]

Domestic transport accounts for around one fifth (11.4 million tonnes in 2017) of Finland's total greenhouse gas emissions, and road transport accounts for 95% of this

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[294] http://liikennejarjestelma.fi/palvelutaso/liikennetyypit/kotimaan-tavaraliikenne/
[295] http://liikennejarjestelma.fi/palvelutaso/liikennetyypit/ulkomaan-tavaraliikenne/
[296] https://www.stat.fi/til/kttav/2018/kttav_2018_2019-04-16_tie_001_en.html
[297] http://liikennejarjestelma.fi/palvelutaso/matkojen-ja-kuljetusten-palvelutaso/tiekuljetusten-kustannustehokkuus/
[298] Lapp et al. 2018: Valtakunnalliset liikenne-ennusteet - Liikenneviraston tutkimuksia ja selvityksiä [National transport forecasts – Research reports of the Finnish Transport Agency].

fifth. Vans and trucks account for around 40% of road transport emissions, equal to around 10% of Finland's total greenhouse gas emissions. A study commissioned by the Finnish postal service Posti indicates that a relatively large share of transport emissions arises from last-mile deliveries. Delivery efficiency has the greatest impact on the emissions of last-mile deliveries, yet vehicle type and distance delivered are also contributing factors.[299]

According to the baseline projection of greenhouse gas emissions from transport, by 2030 greenhouse gas emissions from transport will fall to around 37% of the level in 2005. Underlying the baseline projection are the effects of decisions already made on the likely change in the operating environment, including decisions such as those to increase the share of biofuels and to lower the carbon dioxide emission limit values for new passenger cars and vans as well as heavy-duty vehicles.[300]

The direct emissions from logistics depend mainly on number of kilometres driven, which is why fuel carbon dioxide (CO_2) content plays the largest role in emissions. Fuel CO_2 content can be decreased by increasing the share of biocomponents and the use of electricity. Electrification is expected to extend to an increasing number of transport vehicles as well.[301] The evolution of transport vehicles and their increased energy efficiency also serve to reduce emissions. The maximum length of vehicle combinations, for example, was increased in 2019[302], which was estimated to reduce vehicle-kilometres by 120 million km and CO_2 emissions by 66 million kg, and also to deliver savings of 5–15% in fuel costs.[303]

Digitalisation also plays a role in the development of transport vehicles and emissions. Vehicle manufacturers have introduced innovations such as autonomous trucks, the practical application of which consists of platooning. One of the major players in the field, however, has announced that it will discontinue platooning development to focus on the development of autonomous vehicles, as the benefits of platooning, such as improved aerodynamics and savings in fuel costs, remained below expectations even in ideal conditions.[304] Platooning and the automation of goods transport are not believed to have any significant impact on road traffic volumes but they may result in

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[299] https://www.posti.fi/business-news/tiedotteet/2019/20190605_verkkokauppa_selvitys.html
[300] VTT Technical Research Centre of Finland: Liikenteen kasvihuonepäästöjen perusennuste 2020-2050 [Baseline projection of greenhouse gas emissions from transport 2020–2050].
[301] Sirkiä 2018: Etelä-Suomen hajautetun logistiikkajärjestelmän visio 2030, Uudenmaan liiton julkaisuja C 89 [Vision 2030 in the southern Finland decentralised logistics system. Publications of the Helsinki-Uusimaa Regional Council C89].
[302] https://www.lvm.fi/en/-/maximum-length-of-a-vehicle-combination-34.5-metres-995264
[303] Still 2019: Ajoneuvojen käytöstä tiellä annetun asetuksen muutos - Aiempaa pidemmän ja uudentyyppiset ajoneuvoyhdistelmät [Amended Decree on the Use of Vehicles on the Road – longer and new types of vehicle combinations].
[304] https://media.daimler.com/marsMediaSite/en/instance/ko/Daimler-Trucks-invests-half-a-billion-Euros-in-highly-automated-trucks.xhtml?oid=42188247

transport concentrating on the trunk network of roads.[305] Platooning and other intelligent transport solutions enabled by digitalisation are presented in subsection 8.1.2.

On the one hand, the impacts of digitalisation in logistics directly concern the implementation of logistics, processes and their management, and on the other they are indirect, arising through various change trends. A key component of logistics is information management and information flow throughout the supply chain, and in the logistics sector data volumes are projected to explode in the future. The flow of information safeguards and enables aspects such as delivery tracking in the supply chain as well as timely and correct deliveries. Machine-readable and machine-processed data provides the foundation for automation technology, and accordingly logistics to an increasing extent strives for automated digital communication where the various information systems communicate directly with one another. This sub-sector is the focus of a significant portion of digitalisation development, for example electronic transport order systems. Digitalisation applications and the data economy where business models are based on the utilisation and use of data have been identified to have significant benefits in logistics over the long term.

The importance of data and the data economy is well illustrated in e.g. logistics nodes. Ports, terminals and warehouses are the key logistics chain nodes where deliveries and transport units switch from one transport mode or vehicle to another. Numerous individual actors and businesses typically operate in nodes, and at ports, for example, flows of information between actors and information silos are well-recognised challenges. Digital platforms improve the real-time visibility and interoperability of data, which consequently improves the efficiency and productivity of freight handling, which in turn saves time at logistics nodes and improves transport equipment capacity utilisation and fill rates. The Port of Oulu, for instance, aims to optimise and enhance activities in the port area as well as traffic and goods flows by utilising precise and up-to-date data in its decision-making[306]. Data in the port area in Oulu is collected from multiple sources, analysed and made available for utilisation to the actors and cargo owners in the area. One of the aims underlying this undertaking is to enable the analysis of the port area's climate and environmental impacts and to put port operations on a more sustainable footing.

The most significant benefits of digitalisation are likely derived from the overall improved efficiency of the supply chain. One example of the benefits of digitalisation

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[305] Lapp et al. 2018: Valtakunnalliset liikenne-ennusteet - Liikenneviraston tutkimuksia ja selvityksiä 57/2018 [National Transport Forecasts. Research reports of the Finnish Transport Agency 57/2018].
[306] https://ouluport.com/satamadigitalisaatio-port-oulu-smarter/

can be found in the long-running collaboration between VTT Technical Research Centre of Finland and a leading forest industry company to increase the efficiency of timber transports by optimising the entire raw wood supply chain from stump to mill. The task involves a multiple optimisation problem where ICT plays a critical role: the necessary inputs are data from forest machines generated by IoT sensors, data on woodpile and truck locations generated by satellite positioning, status data on freight trains and the rail network, telecommunications connections, and demanding optimisation calculations on servers. The undertaking resulted in the forest industry company achieving reductions in transport costs and also of 5% reductions in emissions. The company sources 21 million m^3 of timber annually.

Even though automation is being phased into logistics and transportation, the timeline for the deployment and wider adoption of many technological solutions remains to be determined. It has been estimated that relatively little tangible change in logistics performance and implementation will be seen in the foreseeable future.[307] Digitalisation makes development such as port automation possible, but with low goods flows, the costs of investing in automation may easily rise high. In Finland, goods transport volumes are low and geographically scattered in the international comparison, which has slowed down the adoption of automation and digitalisation. However, progress has been made in recent years in areas including warehouse automation and the introduction of various kinds of digital software and open interfaces.

Consolidation of cargo to increase the capacity utilisation rate is one example of the possibilities afforded by digitalisation. Empty runs have remained at an unchanged level despite these possibilities, however. One reason for this may lie in that empty runs are a natural element in many sectors, for example forest industry transports. It is unlikely that digitalisation could deliver any remarkable reduction in empty running by 2030.[308] Nonetheless, the bar to using online platforms for cargo consolidation may be lowered if the platforms can be organically incorporated into the other systems of transport companies. New innovations are most likely to be adopted in the sector when the new functionalities have been seamlessly integrated into existing systems and their benefits are clearly identifiable.

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[307] Pöyskö et al. 2016: Automaatio ja digitalisaatio logistiikassa. Kehitysnäkymiä Suomessa ja maailmalla, Liikenneviraston tutkimuksia ja selvityksiä [Automation and digitalisation in logistics – Development perspectives in Finland and around the world. Research reports of the Finnish Transport Agency].

[308] Liimatainen and Viri 2017: Liikenteen päästötavoitteiden saavuttaminen 2030 - politiikkatoimenpiteiden tarkastelu [Achieving transport emission goals 2030 – investigating policy measures]. The Finnish Climate Change Panel.

9.1.1 Emission-reducing impacts of digitalisation in different scenarios and change trends

Ramboll Finland Ltd was commissioned by the Ministry of Transport and Communications to calculate the impacts of digitalisation on emissions from the logistics sector. The change trends that affect logistics include the following: changes in regulation and technology; urbanisation; globalisation and unitised transport; the circular economy and servicification; and the restructuring of trade. In addition to these identified trends, also unexpected and quickly unfolding events may have significant impacts on the development of logistics digitalisation. The COVID-19 pandemic of 2020, for example, has stepped up pressure to develop digital business and e-commerce in just about every sector.

Logistics digitalisation is manifested by elements such as data collected on means of transport; electronic documents; electronic data environments; logistics automation; real-time situational pictures; and route information. Change trends and the manifestations of logistics digitalisation together have an impact on the total emissions from the logistics sector. The emission indicators in logistics are average consumption, average load, average distance, modal distribution, fuel CO_2 content, and empty runs.

Research data and findings on the impacts of digitalisation on logistics performance and logistics emissions are poorly available, which introduces an element of uncertainty into any calculation of the emission impacts of digitalisation. Ramboll estimated the emission reduction impacts of digitalisation in logistics in respect of the above-mentioned change trends and manifestations of digitalisation in three scenarios, and the examination was divided into two periods: 2018–2030 and 2030–2045. Scenario 1, the basic scenario, presumed that the trajectory of changes in emissions was the same in both periods except for the share of biofuels, which was estimated to rise from the 10.5% in 2018 to 43.5% by 2030 and to 45% by 2045.

The basic scenario is the most likely scenario of the development in transport emissions. In scenario 2, the share of biofuels remains the same as in scenario 1 but advances in digitalisation are made at a more rapid pace than anticipated. The benefits of digitalisation are allocated to consolidated shipments, changes in driving style, engine technology and transport optimisation while at the same time digitalisation has increased transport volumes and emissions due to the growth of e-commerce. The difference between scenario 3 and the basic scenario 1 lies in that in the former, the share of alternative fuels increases somewhat more than anticipated. In scenario 3, biocomponents account for 48% of sold diesel fuel by 2030 and for 54% by 2045. The share of electricity as a fuel in delivery transports is double that in the basic scenario. The greatest emission reductions in all three scenarios are achievable in 2018–2030, while in 2030–2045 impacts towards lower emissions are estimated to diminish.

Regulation and changes in technology

Several studies[309,310] have seen regulation as virtually the only way to reduce greenhouse gas emissions for reasons including the tendency to prioritise cost-effectiveness over emission reductions. Different actors approach digitalisation from their respective starting points and utility perspectives, and regulation can help promote the utilisation and adoption of the solutions and benefits afforded by digitalisation in the sector. In respect of maritime transport, for example, it has been found that significant benefits can be achieved through standardisation and the creation of mutually agreed Application Programming Interfaces (API).[311] The greatest impacts of regulation on emission reductions have been estimated to arise from reducing fuel CO_2 content. Regulation can also steer the development of engine and vehicle technology. The tools of digitalisation in logistics can also enable some regulatory impacts. Data collection and automation, for example, enable changes in driving style and average consumption monitoring, while in respect of route optimisation, data can be enriched with elements such as real-time traffic data.

Digitalisation accounts for a marginal share of the impacts on the total emissions of logistics delivered by the change trend of regulation and changes in technology. As a whole, this trend is nonetheless estimated to deliver the greatest logistics emission reductions in all three scenarios, the trend having the greatest emission reduction potential in scenario 3. Scenario 3 estimates regulation and changes in technology to reduce emissions by 2.12 Mt per year in 2018–2030, with digitalisation accounting for 0.03 Mt per year, and by 0.35 Mt per year in 2030–2045, with digitalisation accounting for 0.01 Mt per year. The corresponding figures in scenario 2 are 1.84 Mt and 0.07 Mt per year (2018–2030) and 0.27 Mt and 0.04 Mt per year (2030–2045), respectively. The basic scenario has the lowest emission reduction potential in respect of regulation and changes in technology: in 2018–2030 emissions are estimated to decrease by 1.80 Mt per year, with digitalisation accounting for 0.03 Mt per year. The corresponding figures for 2030–2045 are 0.25 Mt and 0.02 Mt per year, respectively.

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309 Sirkiä et al. 2018: Etelä-Suomen hajautetun logistiikkajärjestelmän visio 2030, Uudenmaan liiton julkaisuja C 89 [Vision 2030 in the southern Finland decentralised logistics system. Publications of the Helsinki-Uusimaa Regional Council C89].
310 Solakivi et al. 2018: Logistiikkaselvitys 2018, Turun kauppakorkeakoulu. [Logistics report 2018, Turku School of Economics].
311 Rantanen et al. 2019: Digitalization as a tool to reduce GHG emissions in maritime transport. Finnish Transport and Communications Agency Traficom.

Urbanisation

Urbanisation is projected to result in a moderate reduction in logistics emissions. This is because, for example, online shoppers are becoming geographically concentrated, which shortens the average delivery distance and increases the average load. Emissions from the collection of items for recycling are also lower in urban settings. This means the bulk of emission reductions arise from the urban structure, i.e. shorter distances and smaller vehicles. Logistics digitalisation applications such as smart route information can provide opportunities for emission reductions. For example, UPS has developed its own route optimisation application and reported significant cuts in fuel costs.[312] Smart route information can also enable the commercial use of light last-mile delivery vehicles in urban areas and direct them always to the correct door at the property and even inside the property.

Compared with the other change trends, the emission impacts of the digitalisation of logistics in the urbanisation context are greater, but nevertheless only marginal. As a change trend, urbanisation provides the second-highest emission-reduction potential in all of the scenarios. Urbanisation generates the greatest emission reductions in scenario 2, where urbanisation is projected to reduce emissions by 0.14 Mt per year in 2018–2030, with digitalisation accounting for 0.07 Mt per year, and by 0.07 Mt per year in 2020–2045, with digitalisation accounting for 0.04 Mt per year. In scenario 1, urbanisation may enable emission reductions by 0.10 Mt per year in 2018–2030, with digitalisation accounting for 0.04 Mt, and by 0.06 Mt per year in 2030–2045, with digitalisation accounting for 0.02 Mt per year. In scenario 3, the emission reduction potential from urbanisation is estimated to be at the same level as in scenario 1 in 2018–2030, but for 2030–2045 the emission reduction potential is estimated at 0.05 Mt per year, with digitalisation accounting for 0.02 Mt per year.

Globalisation

Increasing globalisation is making business more and more transnational, and a product may be manufactured on one continent while its market is on another. Unitised transport means the carriage of cargo in transport units such as containers, swap bodies and semi-trailers. Transport units form the basis of many transport systems; e.g. container transport, which has been used since the 1960s, is based on standardised transport units. The change trend of globalisation and unitised transport is projected to result in longer average journeys in road transport, as deliveries will head for their destination via a port rather than from a domestic production facility. At the same time, the volumes transported will be higher, which will slightly increase vehicle size and therefore also average fuel consumption. On the other hand, larger

[312] UPS 2020: Orion Backgrounder.

transport capacity is anticipated to increase the average load. Logistics digitalisation applications can also help increase the average load. Capacity estimates and loading rate optimisation are also facilitated by the electrification of waybills. The extensive and consistent use of electronic waybills can improve the loading rate. Efficiency in the logistics sector can also be improved by blockchain technology and electronic data environments, even though the impact on fuel consumption is unlikely to be significant. It is estimated for all three scenarios that digitalisation may potentially offset emissions otherwise increased by the change trend of globalisation and unitised transport.

Circular economy and servicification

In the circular economy, value creation is intangible, with products replaced by services and with raw materials and other material resources kept within the loop. The circular economy is dependent on the benefits brought by digitalisation.[313] As materials are cycled for reuse in the circular economy, logistics systems face new challenges, such as poorer predictability of goods flows and low transport volumes. Therefore one of the requirements for the circular economy is efficient supply chain management enabled by digitalisation, as the increasing prevalence of hiring or borrowing products means an individual item may be transported more and more over its service life.[314] Consumption is projected to shift increasingly from ownership to service use and hire.[315]

The circular economy and servicification are projected to result in a moderate increase in logistics emissions. The growing prevalence and volumes of recycling flows may increase average journeys and transport volumes and lead to recycled products being transported with larger and larger vehicles, which will increase average fuel consumption. On the other hand, loading rates may rise slightly and empty runs decrease due to increasing return transport. It is estimated that logistics digitalisation applications may compensate for some, but not all, of the logistics emissions that increase due to the circular economy and servicification. In all three scenarios, the circular economy and servicification increase logistics emissions by 0.01 Mt per year. The impact of digitalisation on these emissions is minor, with digitalisation not essentially reducing emissions.

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313 https://ek.fi/syty-kiertotaloudesta/mika-ihmeen-kiertotalous
314 https://www.vttresearch.com/en/news-and-ideas/logistics-challenging-circular-economy
315 https://www.sitra.fi/artikkelit/mita-nama-kasitteet-tarkoittavat

Restructuring of trade

A long-running trend in the daily consumer goods trade in Finland has been the concentration of sales to large stores. International and domestic competition provides the impetus for enhancing the efficiency of operations with digitalisation and automation in the trade sector as well, and it is the large businesses in particular that have the necessary resources to do this.[316] In consumer behaviour, the most obvious change has been the rise of e-commerce. As online shopping increases, a growing volume of goods is transported straight from warehouses to customers without any intermediate storage. In Finland, postal service provider Posti estimates that the outsourced logistics market will grow at an annual rate of around 20%, which development is underpinned by the restructuring of trade and the growing demand for services in particular.[317]

As a whole, the restructuring of trade is estimated to increase emissions from logistics. The rise in e-commerce is estimated to lead to longer average distances in deliveries, when customers no longer visit stores to collect their purchases, and also to a decline in average load, when goods are delivered to multiple addresses. On the other hand, this permits the use of smaller vehicles for deliveries, which in turn reduces average consumption. Digitalisation applications in logistics are estimated to reduce the logistics emissions caused by the restructuring of trade. Digitalisation and automation enable the rising prevalence of e.g. parcel lockers and pick-up points, which is estimated to increase average load. Smart and predictive ordering systems, meanwhile, can impact on the number of deliveries and the optimisation of the vehicle stock employed to reduce empty runs and increase average loads. Clients of the Relex supply chain system, among others, have reported significant emission reductions in their supply chains.[318] Intelligent information systems also influence aspects such as number of delivery attempts.

Logistics digitalisation solutions cannot fully compensate for the emissions arising from the restructuring of trade. In scenario 1 as well as scenario 3, trade restructuring is estimated to increase logistics emissions especially in 2018–2030 (0.12 Mt per year in both scenarios). Both scenarios estimate the volume of emissions from the restructuring of trade to turn into decline in 2030–2045, during which the restructuring of trade will increase logistics emissions by 0.07 Mt per year in scenario 1 and by 0.06 Mt per year in scenario 3. In both scenarios and over both periods, digitalisation will reduce emissions by 0.01 Mt per year. In scenario 2, the restructuring of trade is

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316 https://kauppa.fi/uutishuone/2019/08/05/vahittaiskauppa-nyt-suhdannehuipussa-tulevaisuuden-uhkana-yrityskato
317 https://www.posti.fi/private-news/english/current/2019/20190125_transval.html
318 https://www.relexsolutions.com/news/bunting-group-and-relex-win-partnership-of-the-year-at-retail-systems-awards

estimated to increase logistics emissions by 0.11 Mt per year in 2018–2030. Without the impacts of digitalisation, however, emissions would increase by 0.20 Mt per year, meaning that in the scenario, the emission reduction impact of digitalisation in logistics is estimated at 0.09 Mt per year. In 2030–2045 in scenario 2, the restructuring of trade is estimated to reduce logistics emissions by 0.04 Mt per year, with digitalisation contributing 0.04 Mt per year to this.

In respect of digitalisation, electronic data environments are estimated to hold the greatest logistics emissions reduction potential. Their impact is the greatest in scenario 2, where electronic data environments are estimated to reduce emissions by 0.155 Mt per year in 2018–2030 and by 0.075 Mt per year in 2030–2045. The corresponding figures in scenarios 1 and 3 are 0.043 Mt and 0.025 Mt per year and 0.043 Mt and 0.022 Mt per year, respectively. Logistics automation is estimated to hold the second greatest emissions reduction potential, and in respect of this the highest estimated reductions appear in scenario 2. Scenario 2 estimates logistics automation to reduce emissions by 0.074 Mt per year in 2018–2030 and by 0.043 Mt per year in 2030–2045. The corresponding figures are 0.033 Mt and 0.020 Mt per year in scenario 1 and 0.029 Mt and 0.009 Mt per year in scenario 3.

All scenarios estimate that the collection of data on means of transport will reduce emissions by 0.011 Mt per year in 2018–2030 and by 0.006 Mt per year in 2030–2045. The emission impacts of electronic documents and real-time situational pictures are estimated to remain the same in all scenarios and in both periods. Electronic documents are estimated to reduce emissions by 0.001 Mt per year while the impact of real-time situational pictures stands close to 0 Mt per year. Intelligent route information is estimated in scenarios 1 and 2 to reduce emissions by 0.003 Mt per year in 2018–2030 and by 0.002 Mt per year in 2030–2045. In scenario 3, the emissions reduction potential of intelligent route information is estimated to be somewhat higher, 0.008 Mt per year, in 2018–2030, but for 2030–2045 scenario 3 is in line with the estimate in scenarios 1 and 2, 0.0002 Mt per year.

9.1.2 Summary

The most significant logistics digitalisation tools in respect of emissions are those that can have a direct impact on transport volumes and transport performances, i.e. electronic data environments, logistics automation and, to a lesser extent, data collection and utilisation. Digitalisation’s most important contribution to the logistics sector comes from Electronic Data Interchange (EDI) messaging, which can be utilised in planning and cargo consolidation. Smart orders, transparent information and automation, meanwhile, are the engines for change in driving style and the centralisation of distribution.

The digitalisation of logistics enables changes in e.g. average load and average consumption, yet in order to achieve emission reductions, the average load would need to increase to such an extent as to eliminate one whole delivery by vehicle. There have been case examples where digitalisation has delivered emission reductions of several percentage points. On the whole, the effectiveness of the tools of digitalisation in reducing emissions in the logistics sector is fairly low compared to other mechanisms. The most significant among these other mechanisms are influencing fuel switching through regulation and the changes in performance brought about by urbanisation and the concentration of functions.

9.2 Energy sector

ICT is perceived to provide several benefits for the energy sector. The emission impacts are in many respects indirect. For example, the integration of weather-dependent renewable energy production into the power system and market requires digital solutions for the development of new supply- and demand-side flexibility solutions and network management. Entire new solutions and operating models for increased flexibility are developed, especially relating to demand-side flexibility. Digitalisation enables measures such as automated downward adjustment of demand when the price of electricity is high and increasing consumption when the price is low.

Uses specific to the energy management of buildings include ICT applications aiming at behavioural change as well benefits achieved through automation and smart control. Building automation and control systems can utilise self-learning to increase efficiency in energy use. The International Energy Agency (IEA) (2018) has estimated that, by 2040, smart control of the energy consumption of buildings could cut energy use by around 10% (65 PWh) compared with the IEA Central Scenario. While older studies have suggested energy savings in excess of 20%,[319,320] some estimates project considerably lower energy savings attributable to ICT solutions.[321] The greenhouse gas emission savings potential depends on the energy sources used and on the specific emissions of power and heat production.

Impacts of ICT on global greenhouse gas reduction efforts have been estimated in various studies. For example, the Global e-Sustainability Initiative (GeSI) 2015 report

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319 European Commission 2011: Commission Staff Working Document – Impact Assessment. Energy Efficiency Plan 2011.
320 Laitner & Ehrhardt-Martinez 2009: Examining the scale of the behaviour energy efficiency continuum. American Council for an Energy-Efficient Economy.
321 Bastida et al. 2019: Exploring the role of ICT on household behavioural energy efficiency to mitigate global warming. Renewable and Sustainable Energy Reviews.

suggests that rolling out smart energy systems could cut global greenhouse gas emissions by 1.8 Gt CO_2e by 2030 compared with the business as usual scenario. In addition, a further emissions reduction of 1.6 Gt CO_2e is expected to be achieved in energy production when assuming that smart systems can help save up to 6.3 billion MWh of energy. As regards buildings, GeSI estimates that ICT applications could help save 5 billion MWh of energy and cut 2 Gt CO_2e of emissions. However, the methodological approach of the report remains vague, making the calculations difficult to compare. More recent GeSI reports (2020) discuss emission reduction potential more country- and case-specifically and cover global impacts from the qualitative perspective.

The GSM Association (GSMA) (2018) examines the global greenhouse gas emission reduction potential from a slightly different perspective by comparing the situation in 2018 with avoided greenhouse gas emissions enabled by mobile communications. According to GSMA, the enabling impact of mobile communications was estimated to be around 2,135 million tonnes CO_2e – ten times greater than the total annual emissions of the mobile sector (220 Mt CO_2e). GSMA estimates that 10% of the enabled avoided carbon emissions are in the Smart Buildings and 7% in the Smart Energy category.

There is very little comparable and transparently calculated data on the benefits. Measurement-based estimates of the impacts of ICT in greenhouse gas emission reductions are particularly scarce. There are several ecosystem and pilot projects underway in Finland that will produce measured information about energy savings generated by various applications and that will help assess greenhouse gas emission reduction impacts, too.

When assessing the benefits obtainable with ICT in energy consumption and emission reductions, data is also required on the emissions arising from the production of the ICT solution itself. VTT Technical Research Centre of Finland has conducted a few case studies on this and found that e.g. in a 5G base station solar power solution the energy required by the ICT solution itself is only a few per cent of the obtainable benefits.[322] The solution's own energy consumption depends on the way it is used.

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[322] The VTT study containing sample calculations on the benefits of ICT in the energy sector will be published at a later date.

9.2.1 Solutions in heat and power production, distribution and use

Smart grid solutions enable more extensive use of renewable energy thanks to improved demand-side flexibility and therefore help reduce emissions. Electricity networks require a variety of reserves to maintain and secure the system. ICT improves the capacity of the system to receive more wind and solar input. Inverters, frequency converters and controllers of wind and solar installations can also help improve the response of these production forms to power system needs. These measures have significant indirect emission impacts.

In Finland, there is a high level of quality and automation in electricity networks. For example, relative losses in Finnish electricity transmission and distribution are already low in the global context, with no significant emission reductions achievable from these. More accurate monitoring enabled by digitalisation does, however, enable more efficient system optimisation for different situations.

The customer side offers a great deal more opportunities for energy-efficiency improvements and, consequently, emission reductions. Raising customer awareness about their own energy use can alone increase energy efficiency by 10–20%.[323] ICT solutions can also help customers monitor and adjust individual consumption devices more precisely.

The majority of heating systems built or updated in Finland in the 1990s and 2000s take into account factors such as time of day, weekday and outdoor temperature. This would not be possible without digitalisation. For district heating and cooling, digitalisation provides added opportunities for features such as the use of machine learning in the development of demand forecast models, fault diagnostics, preventive maintenance and optimisation of internal heating systems of buildings. Utilising data provided by consumer energy meters in particular offers opportunities for new services and more efficient system management.

District heating companies already commonly use district heating network simulation models and production optimisation systems. Examples of such products include Termis (Schneider Electric, 2020) and DNA District Heating Manager (Valmet, 2020).

Simulation environments referred to as ‘digital twins’ facilitate the implementation of more complex energy systems. A digital twin is a digital replica of a physical entity

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[323] Aydin et al. 2018: Information provision and energy consumption: Evidence from a field experiment. Energy Economics.

that communicates continuously with the physical twin to collect measurement data. A digital twin can be fully data-based and utilise machine learning or, according to the slightly broader definition, be a modelling method that is already currently in use (e.g. a simulation and optimisation model).

In the district heating sector, too, digitalisation often acts as an enabler, i.e. it helps achieve indirect emission reductions. In the case of district heating, developments such as smart building control may be reflected as lower temperature levels in internal heating systems of buildings, which in turn enables lower transmission temperatures in the district heating network. This in turn improves the techno-economic profitability of new low-carbon heat sources, promotes their adoption and may eventually lead into emission reductions.

As a rule, the most efficient way to cut heating costs is to reduce the temperature of a space whenever the space is not in active use. For example, in the UK and Ireland people often switch their heating off when going out, although this means they then return to an uncomfortably cold or minimum-temperature home and experience reduced residential comfort. Smart systems provide a better way of controlling temperatures room by room according to uses and needs – and without compromising comfort. Smart control systems are already available for this purpose.

Heating systems can be controlled remotely, which helps optimise energy consumption for heating. The control of hybrid heating systems, such as oil- and woodchip-fired heating and electric heating as well as various heat pumps, can be based on financial rationale. Domestic hot water can also be heated optimally by e.g. recovering condensing heat from cooling in the summer.

Local energy storage and energy flexibility can be employed to balance production and consumption curves. For example, electric storage heating can be controlled to shift consumption from expensive, high-emission hours to hours when the load is lower.

Smart local systems also allow on-site energy production sources to be utilised optimally. On-site energy production typically means renewables such as solar power. Solar power can also be used in buildings for consumption management and utilising the flexibility provided by the battery system. System optimisation can increase installed solar power capacity and the annual share of on-site production in electricity sourcing. On the other hand, batteries also create energy loss (5–30% lost as heat depending on battery type). The alternative is to inject any surplus into the grid, in which case the emission reduction impact in the energy balance is likely to be greater than the lifecycle emissions from battery manufacture.

9.2.2 Examples from Finland

Smart Otaniemi

The Smart Otaniemi innovation ecosystem focuses on the interface between energy and ICT services. The aim is to look extensively into the opportunities provided by digitalisation and the data economy in the energy context. Key application areas are mobility and buildings.

Data for the Smart Otaniemi platform is collected widely from buildings and other systems in the area. The platform aims to enable the development of and research into novel data-based services and methods. The extensive collection of data on the platform covers areas including energy use, water, weather, indoor and outdoor conditions, and users. The platform is used for the development of a variety of monitoring and optimisation methods, with machine-learning models also employed.

The Smart Otaniemi platform is used to perform e.g. capacity and energy forecasts, energy consumption analyses, heating and ventilation system parameter optimisation, fault diagnostics and visualisation of results.

Buildings in Otaniemi have been modelled in great detail using 3D models based on building information modelling (BIM) concerning features such as structural solutions, building floor plans, technical equipment specifications and various infrastructures. Such digital twin modelling allows measurement data and simulation models to be combined. This way aspects such as impacts of new methods on building status can be examined more freely.

Using the Smart Otaniemi data platform to implement energy efficiency and flexibility creates major opportunities for emission reductions. Most significant opportunities can typically be found in the optimisation of building heating and cooling. Example cases reported have produced energy reductions of up to 10% in cooling and 7% in heating.[324]

Leanheat, Fourdeg, Salusfin and OptiWatti

Several actors (including Leanheat, Fourdeg, Salusfin, OptiWatti) provide equipment and services that consumers can use to control energy consumption and indoor conditions. Some of these (the first three) enable also solutions that provide an

[324] Hasan et al. 2016: Automated optimum geometry generation of a building for the minimization of heating and cooling energy demands. Proceedings of the 3rd IBPSA-England Conference BSO.

implementation model that district heating companies can use for demand-side flexibility. From the district heating company perspective, a demand-side-only concept is useful as it also ensures the efficient functioning of the building's internal heat distribution system, i.e. lower temperature levels as well as good cooling and correct flow rates in the district heating system.

While different actors report average cost savings of 20% with smart control systems, the marketing materials of the companies give percentages even up to 35% or 40%. The actual savings depend on the building and its purpose and manner of use, i.e. the reference level. Residents can, for example, control the temperature of their home room by room and with a timer function. The rule of thumb traditionally employed in Finland is that a drop of 1 °C in indoor temperature cuts heating energy consumption by 5%. Unnecessary heating could be avoided while at work (e.g. 20% the time) and also at night (e.g. 25% of the time). When it is easy to control heating with a device such as a smartphone, a good user interface and a smart control system, the bar to being proactive is lower because ease of use is combined with monetary savings without sacrificing residential comfort.

The potential available in district heating demand-side flexibility is more closely linked to the building and the district heating system. The economic significance may be high if such demand response control enables the significant flattening or cutting of usage peaks. The cost savings potential in the district heating network is, however, estimated to be rather moderate at 0.7%, rising to 1.4% if demand-side flexibility is supported by hot water thermal storage.[325] On the other hand, these savings can be achieved without jeopardising indoor air conditions, or indoor air conditions may even improve.[326] Smart building control and building efficiency can generate not only direct cost savings but also indirect benefits, however.

OptiWatti optimises the electricity sourcing of buildings with electric storage heating using e.g. market-priced electricity and this way creates demand-side flexibility. When demand focuses on hours with a high supply of wind and solar power and the market price is therefore low, emission impacts are also minimised. Other flexibility mechanisms are also available.[327]

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325 Salo et al. 2019: The Impact of Optimal Demand Response Control and Thermal Energy Storage on a District Heating System. Energies.
326 Mishra et al. 2019: Demand response events in district heating: Results from field tests in a university building. Sustainable Cities and Society.
327 https://www.helen.fi/en/news/2017/helen-includes-households-in-the-smart-energy-system

Building system efficiency and control are potentially important factors when moving towards lower transmission temperatures in the district heating network.[328] This in turn facilitates the introduction of waste heat recovery and low-carbon heat sources in district heat production. Businesses providing the product and service can act as key partners of district heating companies when moving beyond the traditional customer interface (the heat distribution centre).

Demand-side flexibility in retail trade

VTT Technical Research Centre of Finland, together with partners, has studied energy savings potential and demand-side flexibility in retail trade using a medium-sized supermarket as an example in a pilot project. The study examined two things: minimising the total amount of electrical energy purchased and used, and levelling out consumption peaks.

As regards the first question, the study examined how much total energy consumption can be reduced, and also how much of the energy consumed can be produced on site with zero emissions using solar panels. Both reductions in total energy consumption and zero-emission on-site production help cut carbon dioxide emissions. The emission value of 100 g/kWh typically applied for Finnish electricity production was used in the calculations. In the future, emissions per kWh from power production are likely to decrease as the shares of zero-emission wind and nuclear power increase. As regards the second research question, the study examined how much consumption peaks can be cut through optimisation based on machine learning, i.e. artificial intelligence. This also creates emission reductions as it is specifically during consumption peak periods that facilities such as emission-generating gas-fired power plants are used.

The amount of purchased capacity decreased by 20–40 kW during daytime hours. This reduction was achieved by optimising the power consumption of the supermarket's system components (freezers, fridges, air conditioning, heating, etc.) through digital control and IoT measurements so as to prevent the components from counteracting each other. Another significant factor was the solar panels installed on the roof of the supermarket.

The typical annual consumption of a grocery store is 600 kWh per square metre. In the pilot supermarket this was cut by 240 kWh/m^2, reducing the share of purchased electricity by as much as 60%. With 1,800 outlets in its grocery store chain, the entire S Group chain consumes 1.1 TWh of electricity per year. Estimating roughly that the

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328 Tunzi et al. 2016: Method to investigate and plan the application of low temperature district heating to existing hydraulic radiator systems in existing buildings. Energy.

S Group could cut half or even as much as 60% (0.33–0.66 TWh) of its electricity consumption, Finland's carbon dioxide emissions would correspondingly be cut by 33,000–66,000 t (using 100 g/kWh as the specific emission of grid electricity).

The calculation is optimistic, as the group's electricity consumption includes facilities other than grocery stores, such as central warehouses, where the savings potential is likely to be lower. Correspondingly, the machine-learning system piloted can help optimise demand-side flexibility. In other words, electricity consumption can be reduced during periods when the price of and emissions from electricity are high. Utilising historical consumption data and sources such as weather forecasts, the system was able to cut consumption peaks by 8.4%.[329]

[329] https://phys.org/news/2017-06-finland-world-energy-saving-supermarket.html

10 Conclusions

This report describes the climate and environmental impacts of the ICT sector in the light of Finnish and international data currently available. The report provides a situational picture that the working group preparing the ICT sector climate and environmental strategy will adopt as a basis for drafting its recommendations and proposals for action.

The ICT sector plays a dual role in terms of climate and the environment. On the one hand, the sector consumes energy and materials and therefore generates emissions, and also impacts on natural environments through e.g. extraction of materials for end user devices; on the other, it enables climate and environmentally friendlier solutions in other sectors and society at large. Digitalisation is seen to occupy a central, perhaps even vital role in the sweeping change that will enable economic wellbeing in a manner that is environmentally sustainable and reduces the greenhouse gas emissions that cause climate change.

Benchmarking the climate and environmental impacts of the ICT sector and monitoring their development presents a challenge, because neither in Finland nor internationally is there in use any systematic, jointly agreed method of reporting the sector's energy or material consumption or its greenhouse gas emissions. Accurate measurement of the benefits generated by the sector is difficult; in many cases, the role of the sector is to enable new approaches and emission reductions. The cross-border nature of the sector, illustrated by the fact that the data we use every day may to a significant extent be processed beyond our national borders, adds further hurdles to obtaining any comprehensive picture. Any assessments made are quickly outdated by the rapid pace of development in technologies and applications.

The scope, availability and comparability of data on the sector's climate and environmental impacts should be improved in order to understand and monitor developments. Data collection and its methods should be improved in a way that helps data to serve its purpose and is also feasible for the actors in the sector.

Based on existing data, it can be seen that, so far, improvement in energy efficiency has helped keep the growth in the sector's electrical energy consumption quite reasonable despite the multiplication of the volume of data transmitted, processed and stored. While recent research articles estimate that the sector accounts for around 7–10% of global energy consumption, lower estimates of around 4% have also been put forward in authoritative sources including the publications of the International Telecommunication Union ITU. The sector's electricity consumption has not skyrocketed in Finland, either, and in fact its share of total consumption here appears to be even somewhat below international estimates.

In global greenhouse gas emissions, the ICT sector accounts for around 1.5–5%. The greenhouse gas emissions from electricity consumption depend on the structure of electricity production. In Finland, electricity production is fairly carbon free by international comparison (2019: 35% renewable, 27% nuclear, largest import source Sweden), which reduces the sector’s carbon footprint here. Moreover, data centre actors and telecommunications companies in Finland are active in sourcing renewable energy, which helps further reduce the carbon footprint of these businesses. Despite the overall electrification development in society, the prospects for the availability of carbon-free electricity are seen as positive in Finland and the carbon footprint of electricity consumption is therefore expected to further diminish in the future. However, the rise in demand has an impact on factors such as the price of green electricity, meaning that energy efficiency may be deemed a goal worth pursuing also in the future.

The introduction of energy-efficient and energy-saving solutions calls for investment and effort. At the same time as new, more energy-efficient solutions become available on the market, existing equipment stock still remains in use. For example, data centres both in Finland and globally are transitioning to cloud services and focusing on larger and more energy-efficient units, yet older data centres and IT areas that relatively speaking consume more energy are still also being used.

Finland’s climate gives it a natural advantage as a location for data centres, since cooling energy accounts for a significant share of a data centre’s energy consumption. Finland also has expertise in the implementation of highly energy-efficient data centres (PUE very close to 1) as well as case examples of how to recover waste heat to heat buildings. Nonetheless, there remains room for improvement in waste heat recovery: recovering the heat generated as a by-product of data centre operation could make a significant contribution to reducing the production of heating energy and consequently to reducing emissions.

As concerns the energy efficiency of software and services supplied with the help of ICT, the topic is only now being broached. Financial incentives should be present for e.g. the production of energy-efficient code in order to encourage experts to put time and effort into this area. Likewise, new technologies are largely developed with starting points other than energy efficiency in mind. Efficient solutions would necessitate attention to these issues at an early stage.

Major material flows are associated with ICT end user devices. The volume of global electronic waste is rising by up to 7% annually. There is little ICT device manufacture in Finland, but in the European frame of reference Finland is a relatively large producer of certain rare metals needed for devices. Going forward, global demand for the high tech metals extracted in Finland may well rise. The Finnish population can reduce the environmental impacts of devices by stepping up recycling, even if it alone is not enough to address the sustainability challenges associated with end user device material flows that recently have commanded attention also at the level of the EU. Metals are the most valuable components of end user devices, which besides them also contain plastic and glass. Recovery often presents a challenge owing to factors including the low valuable element concentrations and assembly techniques.

In future, the ability of energy efficiency development to keep apace with the accelerating growth in data volumes will be key to ICT sector energy consumption. Global internet traffic has been estimated to nearly quadruple between 2017 and 2022. In Finland, the energy efficiency of e.g. mobile networks has improved by a factor of more than five in 2014–2018, while over the same period the volume of data transmitted over these networks has increased more than six-fold. The standards for 5G networks aim for energy efficiency more than 100 times that of the networks' 4G predecessors, yet at the same time the networks will enable data transmission at an unprecedented level and energy efficiency will not automatically translate into declining total electricity consumption. Improved practical energy efficiency of mobile networks is vital to Finland, where the focus is specifically on mobile internet access. As a rule, mobile data transmission requires more energy than data transmission in a fixed network.

An issue at least as vital as energy efficiency development and data volume growth is the future application of data and ICT solutions. In many industries, ICT is also a key enabler of emission reductions. Renewable energy, for example, could not be put to large-scale use without the help of digitalisation. The key questions are whether the potential of the sector can be leveraged to the fullest to reduce energy consumption, materials use and emissions from housing, transport and mobility and industrial production, and what kinds of changes this potential of technology will bring about in the ways we act. The growing prevalence of AI, for example, is seen to hold immense potential for generating new solutions. Besides enabling emission reductions, ICT can support climate change adaptation to the extent that such change can no longer be prevented, and the sector already plays an indisputable role in climate and environmental science as well as in improving fields such as modelling.

Even though ICT does not at present account for any major share of the average consumer's carbon footprint when compared to e.g. residential heating and mobility, there may be considerable variance from one consumer to the next. Consumers may not necessarily be aware of the environmental impacts of their ICT use or of their chances to make a difference in these. A consumer's ICT carbon footprint depends on the numbers and kinds of services used and their usage frequency as well as the connections and devices used for these services. High-resolution video streaming to a large-screen device over a mobile connection consumes more energy than, for example, listening to music on a small-size device with low energy consumption and connected to a fixed network. Consumers could also be more effectively steered to recycle end user devices.

If the potential of ICT in reducing housing and mobility emissions could be better harnessed, this might be of even greater significance. Solutions are already available; residents of individual one-dwelling houses, for example, can reduce emissions by up to tens of per cent by using an IoT solution to control an air source heat pump system relying on renewable energy. Dwellers can also outsource the acquisition and operation of a smart control system designed to manage energy consumption.

Finland has a great deal of expertise both in implementing energy-efficient ICT infrastructure and in developing energy and material consumption-reducing ICT-based solutions for industry and consumers alike. The many solutions provided by Finnish businesses may be seen to hold perhaps even significant export potential associated with greenhouse gas emission reduction.

Appendix

Working group preparing the climate and environmental strategy for the ICT sector

Organisation

Chair and members:

Ministry of Transport and Communications
Päivi Antikainen, Director of Climate and Environment Unit, chair
Atro Andersson, Senior Specialist, member
Aalto University
Jukka Manner, Professor, member
ABB Oy
Timo Kontturi, Director, Sales, member
CSC – IT Center for Science Ltd
Klaus Lindberg, Director, member
Digita Oy
Henri Viljasjärvi, Director, Business Development, member
DNA Plc
Hanna Haapakoski, Sustainability Manager, member
Elisa Corporation
Minna Kröger, Corporate Responsibility Director, member
Finnish Energy
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1. Infrastructure (chair Jarno Ilme, Finnish Transport and Communications Agency Traficom)

2. Applications (chair Jenni Eskola, Finnish Transport and Communications Agency Traficom)

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