CHALMERS
UNIVERSITY OF TECHNOLOGY

Emission Pathways for Information and Communication Technologies

A Study on Swedish Consumption-Based Emissions

Master's thesis in Industrial Ecology

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Abstract

The future climate impact related to Information and Communication Technologies (ICT) is widely debated, with some projections forecasting large increases in greenhouse gas emissions. This study aims to investigate how Swedish consumption-based greenhouse gas emissions from ICT can be reduced. To capture the range of possible futures, an explorative scenario analysis based on prospective life cycle assessment methods is performed. The scenarios are informed by trend analysis, literature search, and interviews. *Premise*, a tool for prospective life cycle assessments, is used to create the life cycle inventory database for future years. The research indicates that low consumption levels and comprehensive energy efficiency gains within the ICT sector result in similar reductions in emissions. Furthermore, the background system, which determines the emission intensity of electricity generation and manufacturing of user devices, influences the emission levels more than the modelled changes in consumption patterns. However, due to the limited scope of the analysed scenarios, as well as methodological issues with modelling the future data centre energy consumption, the uncertainty of these findings is relatively high.

Keywords: ICT, consumption-based emissions, explorative scenario analysis.

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Sofia Wartenberg, Gothenburg, May 2024

List of Acronyms

Below is an alphabetically ordered list of acronyms used in this thesis:

AI	Artificial Intelligence
IAMs	Integrated Assessment Models
ICT	Information and Communication Technologies
IEA	International Energy Agency
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
ITU	International Telecommunication Union
LCA	Life Cycle Assessment
NDCs	Nationally Determined Contributions
OECD	Organisation for Economic Co-operation and Development
PUE	Power Usage Effectiveness
SSP	Shared Socioeconomic Pathway
UEC	Unit Energy Consumption
VR	Virtual Reality
XR	Extended Reality.

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1

Introduction

The vast use of information and communication technologies (ICT) has been a dominating force the last decennia, exemplified by it being titled a technological revolution (Perez, 2010). The expansion of ICT has coincided with rising concerns about climate change, and the interaction between the two becomes increasingly relevant as ICT may act as an enabler of greenhouse gas reducing efforts. The EU has named digital technologies an integral part of the transition towards climate neutrality (European Commission, 2020). According to one estimate by Malmodin and Bergmark (2015), ICT could enable reductions of up to 15 % of global greenhouse gas emissions in 2030. The authors further mention that the potential for avoided emissions is present throughout many sectors, with implementation areas such as agriculture and transportation. Similar messages are present in industry. Recently, several CEOs of large ICT companies signed a declaration which highlights development towards green digital technologies (European Commission, 2023).

However, many uncertainties regarding the climate benefits from ICT remain. According to Freitag et al. (2021), there is a risk that emissions from ICT will increase, especially under circumstances where constraints from policies are lacking. Furthermore, the authors argue that additional policy mechanisms, or initiatives from the sector, are needed for alignment with current climate targets. Similarly, the EU has mentioned that ICT emissions could reach 14 % of global emissions in 2040 if left unregulated (European Commission, 2020). This would be a drastic increase considering that current estimates ascribe roughly 2 % of global greenhouse gas emissions to ICT (Freitag et al., 2021). The issue is further exacerbated when acknowledging historical patterns of rapid growth in the ICT sector. For example, the number of internet users almost doubled between 2015 and 2022, according to the International Energy Agency (IEA, 2023). Simultaneously, internet traffic increased with 600 % (IEA, 2023). Additionally, Freitag et al. (2021) argue that emerging technologies such as artificial intelligence (AI), big data, and internet of things (IoT) have the potential to drastically increase ICT-related emissions.

In summary, the future development of the ICT sector's climate impact is uncertain. To capture the wide range of possible futures, explorative investigation of emission pathways can be used. The aforementioned call for policy intervention (see Freitag et al. (2021)), and the state's role as a key legislator, further motivates country-level analyses. A relevant case study is Sweden, which is both a large exporter and consumer of ICT. For example, both Meta and Microsoft host data centres in

Sweden (RISE, 2023). Additionally, in Sweden, the percentage of ICT employees in relation to the business sector in general exceeds the average in the Organisation for Economic Co-operation and Development (OECD, 2024). The consumption level is indicated by that the country's ICT Development Index, a figure which incorporates factors such as internet access and mobile broadband subscriptions, is above the European average (International Telecommunication Union [ITU], 2023). Finally, in light of the Swedish Committee on Environmental Objectives' suggestion to establish a national target for consumption-based emissions (Swedish Government, 2022), an analysis of Swedish consumption-based emissions from ICT is warranted.

Beyond the uncertain development of the ICT sector, lack of open and current data also poses an issue when estimating the climate impact of the sector. This problem has, for example, been highlighted by Koomey and Masanet (2021) and Mytton and Ashtine (2022). To strengthen the scenario analysis methodology, indicators that serve as proxies for future developments in the sector could be useful in lack of possibilities of modelling all activities in the sector explicitly. These proxies should aim to capture significant impacts of future developments on the material and energy consumption of ICT. The identification of key indicators could also facilitate continuous monitoring of the sector's climate impact, without inducing too high of a reporting burden on the sector's actors.

1.1 Aim

The aim of the thesis is to investigate how Swedish consumption-based greenhouse gas emissions from ICT products and services can be reduced.

1.2 Research questions

To fulfil the aim of the study the following research questions will be answered:

- What proxies can be used to estimate the material and energy consumption connected to future ICT products and services?
- What different scenarios are relevant for studying future reductions of emissions from ICT?

1.3 Ethical, societal, and ecological considerations

The overarching goal of the study is to enable better environmental policy making for the ICT sector by exploring future emission pathways. Therefore, it naturally concerns both societal and ecological aspects and subsequently the thesis has been designed to strive for a fair and impartial survey of the subject. Due to the risk of misinterpretation of futures studies, the limitations and explorative purpose of the thesis are to be clearly communicated throughout the work. To avoid skewing the information gathered through personal communications, the affected person was given the opportunity to approve the formulations in the thesis prior to publication. No other ethical, societal, or ecological considerations of importance have been identified.

2
Theory

Considering that the aim of the study is future-oriented, a description of futures studies is motivated. In 1996, Bell defined it as follows:

> ”A new field of social inquiry has been created whose purpose is the systematic study of the future. (...) Futurists aim to discover or invent, propose, examine and evaluate possible, probable and preferable futures”.

The notion that futures studies is a distinct field has since been contested, for example by Marien (2002). Nevertheless, Kristóf (2024) argues that the discipline has existed in the scientific sphere since the beginning of the twentieth century. Kristóf also points out that futures studies has connections to many different topics, ranging from military strategy to environmental sustainability. A commonly used concept within futures studies is scenarios (Börjeson et al., 2006), which has been utilised in this project.

2.1 Scenario analysis

Scenario analysis can be used to study the future of a system. Its use within the environmental community at least dates back to the release of *Limits to growth* in the 1970s (Alcamo, 2008), which studied society and the environment through the lens of different futures. Within this field, scenarios can, among other things, be used to communicate complex environmental information, aid policy making, and increase awareness about environmental problems (Alcamo, 2008).

According to Postma and Liebl (2005), scenarios differ from forecasts in that they aim to analyse uncertainties, rather than elements which are likely to prevail. Börjeson et al. (2006) proposed a scenario typology, dividing the field into predictive, explorative, and normative scenarios. The aim of this study largely corresponds with the explorative category, aiming to answer the question *what could happen?*. According to the authors, this type of scenario is suitable for capturing radical transformations and longer time scales. Börjeson et al. (2006) further identified three steps in the development of scenarios: generating, integrating, and consistency. These capture the idea generation through for example surveys and workshops, the integration of data into (mathematical) models, and lastly, the investigation of whether the scenarios are consistent.

2.2 Prospective life cycle assessment

To quantitatively model scenarios for future emissions, tools for assessing the environmental impact of products and services are needed. Commonly, life cycle assessment (LCA) is used for this purpose. However, conventional LCAs are not suitable for studying future systems, as they build on current practices of production, transportation, use, and disposal of materials and energy. Instead, prospective LCA, which is adapted for studying future systems (Arvidsson et al., 2018) can be used. To conduct a prospective assessment, a two-layered system model is commonly used. The layers typically consist of a foreground system, which concerns the use and production of the technology, and a background system, where underlying factors such as global climate policy and energy mix are included. With similarities to the scenario typology proposed by Börjeson et al., Arvidsson et al. put forward two types of foreground system models for prospective LCAs: predictive scenarios and scenario ranges. The latter largely corresponds to the aforementioned explorative scenarios.

Although the literature contains manifold prospective LCAs, ranging from clothing items to wind power turbines (Arvidsson et al., 2018), the field is new. In lack of a general methodology for prospective LCAs, Thonemann et al. (2020) conducted a review study aiming to develop a framework for these assessments. The study emphasised three challenges: comparability, uncertainty, and data. To address these issues, the authors proposed measures that include, but are not limited to, using expert interviews and literature to tackle issues with data availability, assessing the system from cradle-to-grave, performing sensitivity and uncertainty analyses, and stating the maturity of the technology under investigation.

Furthermore, Thonemann et al. (2020) mention that the background system can be developed through incorporation of integrated assessment models (IAMs). Sacchi et al. (2022) have created a tool called *premise* for prospective LCAs, which uses IAMs to transform life cycle inventory databases for future years. IAMs quantitatively connect changes in society and the economy with the earth system. The shared socioeconomic pathways (SSPs), which are used in assessments done by the Intergovernmental Panel on Climate Change (IPCC), have been utilised as a basis for IAMs and describe different possible developments of society in the future (IPCC, 2021). There are five different SPPs which depict a range of different paths. For example, SSP1 represents a sustainable development with decreasing resource use and inequalities, while SSP5 entails a continued high use of fossil fuels and focus on economic growth (Riahi et al., 2017). The pathway SSP2 is built on historical trends and represents a mid-way scenario.

3

Methods

To address the research questions and aim, a prospective LCA framework is used to explore different emission pathways for the ICT sector. The scenarios are modelled using a two layered system model, consisting of a foreground and a background system. An overview of the project's methods is shown in Figure 3.1. In the following sections these methodological steps are elaborated, beginning with the overarching research approach.

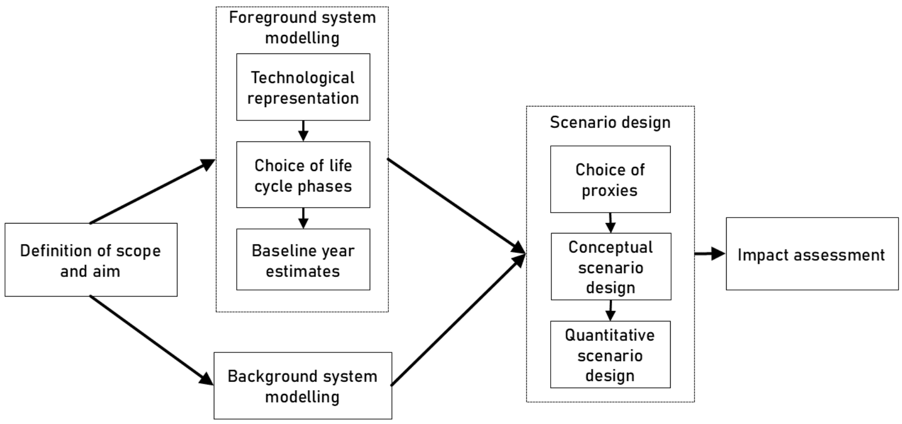

Figure 3.1: Overview of the used methods, including the scope and aim definition, the system modelling, the scenario design, and the final impact assessment.

3.1 Research approach

As the study aims to provide a broad understanding of emissions tied to ICT, the functional unit is defined as the Swedish consumption of ICT products and services by individual consumers. Hence, ICT products and services used by companies and public organisations are excluded. The study will not quantify scope four emissions, also called avoided emissions, connected to the ICT sector. Moreover, emissions from supporting activities, such as heating of office buildings, employee travel and similar will not be considered. Regarding the scenario development, the study will focus on establishing upper and lower bounds on future emissions and will therefore aim for generating possible, rather than likely emission pathways.

Due to the interdisciplinary nature of the study, drawing from fields such as ICT, futures studies, and environmental systems analysis, a mixed-methods approach was deemed most suitable. This is in line with recommendations by Arvidsson et al. (2018), which encourage researchers to use a plethora of different resources, such as patents, interviews, and scientific literature.

Initially, review studies were used to get an overview of the subject, most notably the ones written by Freitag et al. (2021) and Bieser et al. (2023). The studies provided a summary of previously used methods for estimating the sector's emissions and potential drivers of future emissions. These findings, along with other literature such as Andrae (2019), were used for the overarching method and design of the foreground system model. The baseline year data needed for the foreground system model was primarily retrieved from the studies by Malmodin et al. (2024) and Farfan and Lohrmann (2023), along with statistical databases such as Statista.

To complement the perspectives found in the literature, three experts were consulted to get an indication of valuable resources and perspectives. These experts included one researcher specialised on data centres, one LCA researcher who studies emissions from ICT, and lastly, one researcher who studies futurology and AI safety.

Beyond literature and interviews, trend analysis was utilised to get an idea of previous developments within the ICT sector. For example, historical trends and projections in user device sales and penetration rates of technologies were taken from Statista. Additionally, ICT use time estimates from Urban et al. (2021) and Nordicom, University of Gothenburg (2020) were also studied. These were complemented with projections and historical estimates of data traffic and data centre workloads from IEA (2023), Cisco (2018), and Jakopin et al. (2023). Lastly, advertisements and reviews of emerging technologies were used to get a sense of the maturity of the technology, for example an advertisement for the Apple vision pro (see Apple (2023c)) was studied.

For the scenario design and foreground system modelling, the information collected from the literature, the experts, and the trend analysis was synthesised and translated into a quantitative model. The background system was modelled using premise, a tool for generating life cycle inventory databases for prospective LCAs (Sacchi et al., 2022). To conclude the scenario modelling, the foreground and background system models were combined by multiplying the calculated emissions per product or energy unit with the total consumption of that unit. The energy consumption from data centres and networks was multiplied with the global electricity emission factor. Furthermore, the energy consumption from user devices was multiplied with the Swedish electricity emission factor. Lastly, the emissions from all categories were added to yield the total emissions from consumption of ICT in Sweden. These values were then divided by the Swedish population in 2020 to get the consumption-based emissions per capita.

3.2 Foreground system modelling

In the following sections, the methods used for the modelling of the foreground system are presented. Firstly, the technological representation is determined, meaning the selection of technologies which are chosen to represent the system. Secondly, the most emission intensive life cycle phases are mapped out and included in the model. Then, an estimate of the material and energy consumption in the baseline year, set to 2020, is presented. For the user devices, the used stock-flow model is also described. Detailed accounts of the data, sources, and assumptions used for the foreground system model can be found in Appendix A.

3.2.1 Technological representation

In a recommendation by the ITU (2018), the ICT sector is divided into end-user goods, network goods, data centres, and services. Building on this definition, the following categories are included in the scope of this study:

- User devices
- Data centres
- Networks.

The ICT service category, which includes for example IT consultants, is omitted as it connects to the supporting activities which are excluded as per the limitations of this study. In line with ITU recommendations, paper media is excluded from the scope. However, contrary to the recommendations, televisions are included. As video content is available on other devices than televisions, this inclusion facilitates the allocation of emissions. Previous publications have both included (Andrae & Edler, 2015) and excluded (Malmodin et al., 2024) televisions from ICT. Blockchain, which is sometimes associated with ICT, is excluded from the scope.

Only devices that currently account for a significant part of the sector's carbon footprint, or that connect to emerging technologies are included in the study. Previous estimates by Malmodin et al. (2024) were used to identify these devices. Those that account for more than 5 % of either the sector's embodied emissions or the use stage emissions are included. Examples of these devices are customer-premises equipment, smartphones, and televisions. The customer-premises equipment includes for example routers and modems and are devices which consumers use to connect to network services.

Furthermore, extended reality headsets (XR headsets) and wearables are considered since they are emerging technologies that also can be used for communication, rather than solely for entertainment. Additionally, two IoT devices, smart speakers and surveillance cameras, listed by Malmodin et al. are included to represent the emergence of IoT. A summary of the chosen user devices is shown in Table 3.1. The table is divided into two categories: devices that previously have accounted for a significant impact (traditional), and those which might cause a considerable future impact (emerging technologies).

Table 3.1: User devices that are included in the study, sorted by if they are traditional or emerging technologies.

Traditional devices	Smartphones Tablets	Desktop PCs Laptop PCs	PC monitors Televisions	Customer-premises equipment
Emerging technologies	Smart speakers	Security cameras	Wearables	XR headsets

3.2.2 Considered life cycle phases

To maintain sufficient simplicity in the study, only the most emission-intensive life cycle phases for each of the three ICT categories are considered. Starting with the user devices, previous studies have found that the production and use phase contribute most in terms of greenhouse gas emissions (Arushanyan et al., 2014; Clément et al., 2020). The two phases account for roughly the same amount of emissions (Malmodin et al., 2024), which motivates including them both in the study. According to Ficher et al. (2024), the modelling of the end-of-life of digital equipment is not yet standardised and requires further development. The authors also note that some of the current methodological choices lead to underestimation of the impact of the end-of-life. Due to the lack of consensus regarding the treatment of this life cycle phase, the end-of-life is not considered in this study.

For both data centres and networks, the use phase dominates the emissions of greenhouse gases. In 2020, more than 70 % of data centre related emissions, and 80 % of network related emissions, came from the use phase when excluding end-of-life emissions (based on (Malmodin et al., 2024)). Subsequently, only the use phase emissions from these two categories are considered in this study.

3.2.3 User devices

To analyse the emissions from the manufacturing of user devices, the number of purchased units in Sweden for each product type was multiplied with estimates of the emissions per produced product, taken from the background system. The sales per product type for the baseline year, 2020, were retrieved from Statista (2024).

Likewise, the use phase emissions were estimated by multiplying the total energy consumption from user devices with the emission intensity of the used electricity, as determined by the background system. The user devices' energy use, E, in year T was calculated according to

$$E_T = \sum_i S_{i,T} \cdot \mathrm{UEC}_i, \tag{3.1}$$

where i represents the product type, $S_{i,T}$ the active stock of that product in year T, and UEC_i the unit energy consumption per year. The UEC was retrieved from a study by Urban et al. (2021), which investigates the use of electronics in American homes. As the study was performed during the COVID-19 pandemic, a share of the measured energy consumption is related to remote working. To remain consistent with the focus on consumption-based emissions, energy use related to work activities was excluded from the UEC. This was done by scaling the UEC in 2020 with the use time values for 2017 reported in the same study. As the average use time for televisions in Sweden deviated from the American values, this UEC was also rescaled after the Swedish use time. A summary of the user device parameters, including the UEC, is shown in Table 3.2.

Table 3.2: Input parameters per product for the user device foreground system. Here, λ and κ represent the scale and shape parameters for the Weibull distribution.

Product	λ	κ	UEC [kW h/year]
Smartphone	3.53	1.83	4.5
Tablet	5.18	0.88	6.1
Laptop	7.50	4.59	36
Desktop	6.60	1.97	220
PC monitor	6.45	3.75	62
Customer-premises equipment	6.45	3.75	102
XR headset	3.53	1.83	22
Security camera	6.45	3.75	31
Smart speaker	3.53	1.83	22
Wearable	3.53	1.83	0.5
Television	8.98	3.06	61

A stock-flow model was designed to estimate the number of products in the active stock. The model is based on a study on ICT products in Denmark by Zhilyaev et al. (2021) and was implemented in Python (version 3.11.7). The active stock was calculated as follows

$$S_{i,T} = \sum_{t=1990}^{T} p_i(t) \cdot W_i(T-t), \tag{3.2}$$

where the start year was chosen in line with the assumptions made by Zhilyaev et al. In the equation, $p_i(t)$ is the number of purchased products in the year t, and $W_i(T-t)$ is the survival function for the Weibull distribution, which represents the probability that a product is still in use after $T-t$ years (Zhilyaev et al., 2021).

A logistic, S-shaped, function was used to model the number of purchases for all years before the baseline year. This function was chosen as it is considered to capture a common diffusion pattern of new technologies (Grübler, 1998). The products were divided into two waves: first wave products like televisions and desktop computers which were used before the 2000s, and second wave products like smartphones, tablets, and smart speakers which were introduced in the 2000s. To account for this difference, two S-curves were constructed, where the newer wave product sales were displaced by 10 years. Both product types were assumed to reach the recorded number of purchases in 2020, however, the diffusion of the second wave products was assumed to be faster. To summarise, the number of purchases $p_i(t)$ for product

i and year t was described with the following function

$$p_i(t) = \begin{cases} \frac{p_i(t=2020)}{1+e^{-0.5(t-2000)}}, & \text{for } 1990 \leq t < 2020 \text{ if } i \text{ is a first wave product} \\ \frac{p_i(t=2020)}{1+e^{-(t-2010)}}, & \text{for } 1990 \leq t < 2020 \text{ if } i \text{ is a second wave product.} \end{cases} \tag{3.3}$$

A summary of the classification of products into first and second wave, as well as the number of purchased products in 2020 is shown in Appendix A.

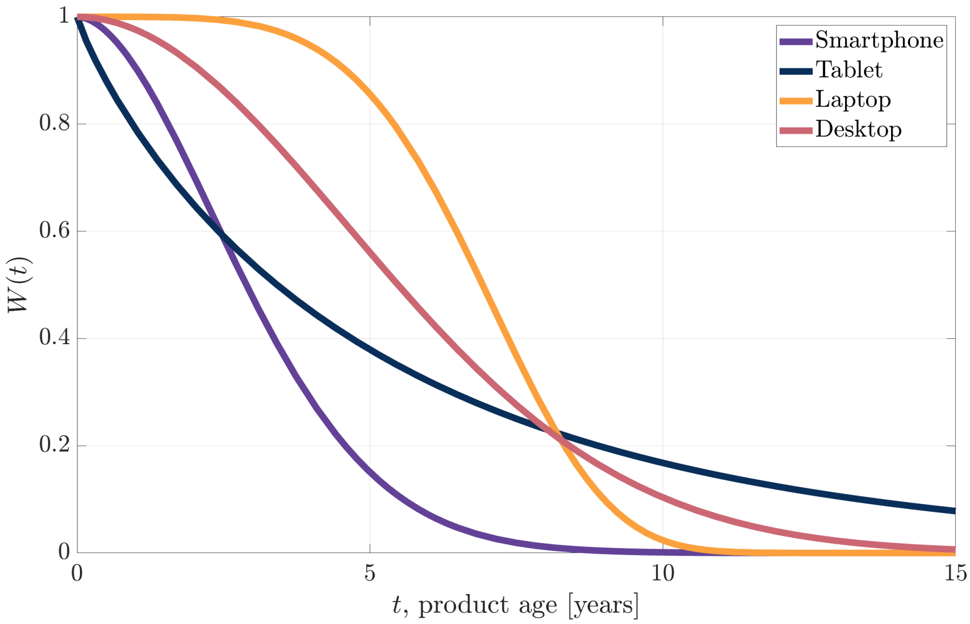

Figure 3.2: The Weibull survival function, $W(t)$, for some of the analysed user devices.

The Weibull survival function is defined as unity minus the cumulative density function for the Weibull distribution, and can be expressed as

$$W_i(t) = e^{-(t/\lambda_i)^{\kappa_i}}, \tag{3.4}$$

where λ_i and κ_i together determine the function and therefore the characteristics of the product's survival. For smartphones, tablets, laptops, and desktops, the parameter values were taken from Zhilyaev et al. (2021). As the calculations aimed to capture the use phase energy use, the values for the service life, rather than the storage life, were applied. For the smartphone, the "smartphone era" parameters were used as they were thought to best represent the current market. The parameters for PC monitors and televisions were based on findings from Kalmykova et al. (2015). The remaining products, for which no literature was found, were modelled based on products with assumed similar lifetimes. Therefore, wearables, smart speakers, and XR headsets were assigned the same parameters as smartphones, and customer-premises equipment and security cameras the PC monitor parameters. To illustrate the effect of the Weibull parameters, Figure 3.2 shows the Weibull survival function for some of the user devices.

3.2.4 Networks

To estimate the energy consumption from networks in the baseline year, two types were considered: mobile and fixed broadband networks. Fixed telephony was excluded to simplify the calculations, motivated by it constituting less than 10 % of the total network energy consumption (based on Malmodin et al. (2024)). Moreover, only private subscriptions were included to ensure that only end uses by private individuals are considered. The energy use was calculated by multiplying the number of subscriptions with the energy use per subscription. For the energy use per subscription, only the access network and core network energy consumption were included. The support activities were excluded as per the limitations of this study. In Table 3.3 the data used to calculate the energy consumption is disclosed. Note that no regional differentiation has been made, meaning that the energy use per subscription is the global average.

Table 3.3: Data used for calculating the network energy consumption in the baseline year. The number of subscribers is taken from the Swedish Post and Telecom Authority (2023), and the energy use per subscription is based on findings from Malmodin et al. (2024).

Subscription type	Number of subscribers	Energy use per subscriber and year [kWh]
Mobile	10 435 000	18
Fixed broadband	4 013 000	47

The calculations for the baseline year yielded a network energy consumption of around 380 GW h for Swedish end uses by private individuals. To corroborate this estimate, a comparison with values from Farfan and Lohrmann (2023) was made. The study only discloses the sum of network and data centre energy related to Swedish subscriptions but assumes a data centre-to-data transmission network ratio of 1.33. Reversing the calculations gives that 57 % of the energy should be allocated to the networks. As Farfan and Lohrmann provide a range of values, the average between the maximum and minimum value was used. Implementing these assumptions yields an energy consumption of 710 GW h in the baseline year. However, the study includes business use. Based on projections from Cisco (2018), approximately 72 % of the global data traffic is consumer related. Multiplying the value from Farfan and Lohrmann with this factor gives an energy use of 510 GW h. Although this value deviates from the previous calculation, which yielded an energy use of 380 GW h, it indicates that the order of magnitude is reasonable.

3.2.5 Data centres

As few studies focus on data centre energy use from Swedish consumption, this baseline value was approximated using the previously calculated network energy use. By applying the same data centre-to-data transmission network ratio of 1.33 as used in Farfan and Lohrmann (2023), the data centre energy consumption was calculated to $\frac{380\,\mathrm{GW\,h}}{1.33} \approx 290\,\mathrm{GW\,h}$. Similarly as for the networks, the calculation was compared to other estimates, this time with the values presented in Malmodin et al. (2024). The comparison was made by multiplying the data centre energy consumption reported by Malmodin et al. with the share of Swedish internet users among global users. This gave an energy consumption of 440 GW h. Once again, the value indicates that the order of magnitude is reasonable, but that considerable uncertainties are prevalent.

3.3 Background system modelling

The background system model was constructed using a database called premise (version 1.8.2), made specifically for prospective LCAs (Sacchi et al., 2022). Through implementation of this tool, a thorough background system model could be used despite the limited time frame of the project. In premise, IAMs and ecoinvent are combined to create a life cycle inventory database suitable for LCA studies of future systems. The values in the database are related to the IAMs through sector-wide transformations, which for example implement improvements in electricity generation efficiency or steel production efficiency. For this project, the general function ”update” was used, which performs all available sector transformations in premise, except those related to cars, busses, and two wheelers. This comprehensive transformation was chosen as it results in a large inclusion of the IAM scenarios into the database. However, to maintain simplicity, the standard ”update” function was used instead of additionally including the aforementioned transport transformations.

In addition to the transformations, the background system also depends on the choice of SSP and IAM. For this project, the SSP2-NDC REMIND scenario, which builds on historical trends in societal development, was chosen. This pathway also includes the ambitions cemented in the nationally determined contributions (NDCs), which have a fundamental role in the implementation of the Paris Agreement. Given that this pathway largely represents current climate change mitigation ambitions, it was deemed suitable as a mid-way pathway. However, to analyse the wide range of possible outcomes, SSP5-Base and SSP2-Pkbgt1150 were also tested. These two pathways were used to represent a high- and low-emission scenario respectively. Lastly, calculations were also made using a constant background system which was based on the baseline year. This background system scenario is referred to as ”status quo”.

The premise databases were generated for every fifth year between 2025 and 2030 using ecoinvent (version 3.9.1 cut-off). Brightway (version 2), an open-source package for performing LCA calculations in Python, was used for the calculations of the emissions per product. In Brightway, the method ”IPCC 2021, climate change”, which uses global warming potentials with a 100-year time horizon from the latest assessment report (AR6) from the IPCC, was used. For the products that were missing in ecoinvent, estimates were taken from other sources. To adjust these values after the chosen pathway, they were extrapolated by reducing the emissions in line with the emissions from the smartphone manufacturing. For the customer-premises equipment, the embodied emissions were not calculated due to a lack of up-to-date data. However, estimates from Malmodin et al. (2024) indicate that this life cycle phase constitutes a small part of both total ICT and customer-premises equipment emissions.

The emissions from Swedish electricity were assumed to decrease linearly between the baseline year and 2035. This adjustment was made because premise reported remarkably higher values for the first years when compared to the baseline year and other sources. For example, premise gave an emission intensity of 300 g CO_2eq per kW h for 2020, while reported values are closer to 90 g CO_2eq per kW h for Nordic electricity (Sandgren & Nilsson, 2021). This is likely because premise does not have country-specific models, meaning that the Swedish values are based on estimates for Europe.

The calculated values for the greenhouse gas emissions per product are shown in Table 3.4. A summary of all the data used for the background system model is presented in Appendix C.

Table 3.4: Emission intensities in kg CO_2eq per unit consumption for the SSP2-NDC pathway. The electricity values correspond to a use of 1 kW h, and the consumer electronics to the embodied emissions of one sold unit.

Product	2020	2025	2030	2035	2040	2045	2050
Global electricity medium voltage	0.71	0.35	0.23	0.15	0.084	0.044	0.030
Sweden electricity low voltage	0.044	0.040	0.036	0.032	0.027	0.025	0.016
Smartphone	39	22	16	13	10	8	7
Tablet	88	50	37	30	23	18	17
Laptop	170	100	80	60	50	40	40
Desktop	220	140	110	90	70	60	60
PC monitor	380	380	200	180	160	140	110
XR headset	230	170	120	100	70	60	50
Security camera	68	50	37	29	22	18	16
Smart speaker	60	44	32	26	19	15	14
Wearable	25	18	13	11	8	6	6
Television	380	240	190	160	130	110	100

4

Scenario design and method development

In this chapter, the results from the scenario design are presented and discussed. The findings entail a conceptual scenario design, in which an overarching theme for each scenario is defined, as well as an analysis of proxies which can be used for estimating the future material and energy consumption of ICT. Lastly, a quantification of the foreground system scenarios, based on the previous findings, is presented.

4.1 Analysis of proxies for the scenario design

To facilitate the quantitative foreground system modelling, proxies for the future material and energy consumption of the ICT sector are analysed. Starting with the energy use of data centres and networks, many different proxies, such as the number of subscribers (Farfan & Lohrmann, 2023), data traffic (Andrae, 2019), and number of operations (Andrae, 2020), have been suggested and used. Common bottom-up approaches, such as modelling the energy consumption via the number of installed servers (see for example Malmodin et al. (2024)), are difficult to connect to scenarios rooted in consumer behaviour. On the contrary, the number of subscribers is easy to relate to consumers, and statistics on the metric are readily available from the Swedish Post and Telecom Authority. Therefore, this metric was used for the modelling of the network energy consumption in the baseline year. However, Andrae (2019) criticised the use of subscribers as a proxy, as the increased use of IoT will likely make it more difficult to define ”a subscriber”. Therefore, data traffic, which Andrae (2019) suggested as a proxy for network energy consumption, is considered more robust to model the development for subsequent years. In the study, Andrae assumed a proportional relationship between data traffic and energy use. The author further included the electricity intensity in the equation.

However, using data traffic as a proxy for network energy consumption can be criticised. Koomey and Masanet (2021) specifically highlight the issue of non-proportionality between data demand and network energy consumption. Access networks are designed to always be able to meet peak capacity (Aslan et al., 2018), which naturally affects the proportionality between the energy consumption and data traffic. According to Morley et al. (2018), data traffic varies substantially during the day, which further strengthens the argument. Despite this discussion, data traffic is still deemed the most suitable proxy for this study, as it is easier to capture changes in user behaviour with data traffic when compared to the number of subscribers. Additionally, estimates of yearly consumption, rather than hourly energy consumption, lessen the severity of the non-proportionality. It is, however, important to note that a large change in the peak load characteristics will likely undermine the usage of data traffic as a proxy. This caution is especially relevant as Morley et al. (2018) have observed a faster increase in peak hour data traffic compared to the average.

For data centres, the use of proxies is even more complicated. In 2020, Andrae pointed to operations as a better metric than data traffic for estimating energy use from computations. In this context, the author also highlighted possible implications of machine learning, which could require a larger number of computations per transmission volume. To be a relevant proxy for this study, operations or computations should preferably track well with other functions of the data centres, such as the storage and communication volume. This was not the case for the period 2010 to 2015 (based on Andrae (2019)). However, as the energy consumption from storage is a relatively small share of total data centre energy consumption (based on Masanet et al. (2020)), it still might be a useful proxy. Another issue with using operations is the distance to the end user. To fully utilise this as a proxy, different user applications would need to be expressed in terms of operations. In lack of literature on the topic, no one proxy was deemed comprehensive enough to use on its own. Currently, combining different methods is a more realistic approach. The methods used in this study for estimating the data centre energy use are further elaborated in section 4.3.3.

In the context of developing proxies for the energy use from data centres and networks, it is important to note that previous studies have been criticised for using overly simplified models (see Koomey and Masanet (2021)). According to Koomey and Masanet (2021), these models have led to inaccurate estimates of the climate impact of ICT. The authors identify a few common issues with these types of analyses, including using old data, extrapolating short term trends, and assuming proportional relationships on weak basis. Considering that the discussed proxies largely rely on proportional relationships which are established on uncertain data, the mere possibility of creating a proxy for data centre and network energy use can be questioned. Evidently, there is still no proxy that is widely accepted as well as sufficiently comprehensive. Even if there were, data availability would likely still pose as a considerable challenge.

For the emissions from the manufacturing of user devices, the need for proxies is not as large as for the other ICT categories. This is partly due to the availability of product-differentiated purchasing statistics. As the purchasing of user devices is close to consumers, the system is also easy to understand and subsequently model. Therefore, no proxy is needed to quantify this category, instead a bottom-up approach is considered sufficient. For the user devices' use phase emissions, the use time is used as a proxy. Through the use time, a change in the UEC can be estimated. In combination with the aforementioned stock-flow modelling, which has been tested for ICT products (see for example Zhilyaev et al. (2021)), the use time can be incorporated in the estimates of the total energy consumption. Additionally, the use time influences the consumption of network and data centre services. Therefore, the effects of use time increases can also be used in the modelling of networks and data centres. Further strengthening the relevance of use time for ICT-related emissions, it was applied in a recently published study which investigates the environmental impacts of consumption of digital content (Istrate et al., 2024).

4.2 Conceptual scenario design

In this study, three different scenarios are considered in order to capture the wide range of possible pathways that future consumption-based ICT emissions could follow. In these scenarios, two different consumption levels are represented. Firstly, an intensified use of ICT products and services is modelled, hereby called the *intensified ICT use scenario*. Secondly, the lower consumption level is represented by a shift towards multi-functionality, a scenario defined as *shifting towards multi-functional ICT*. As the recent decades have shown a vast increase in ICT use, the low-consumption scenario is largely based on current consumption patterns. To be able to compare the constructed scenarios to climate targets, the temporal boundary is set to the year 2050, five years after the proposed Swedish net-zero target for consumption-based emissions (Swedish Government, 2022).

Beyond changes in the demand for products and services, future efficiency gains are also modelled. Earlier studies on the future resource consumption of the ICT sector have received criticism, see for example Masanet et al. (2020), for neglecting efficiency gains. Historically, efficiency gains in data centres and networks have partly counteracted the drastic increases in service demands (IEA, 2023; Masanet et al., 2020). Between 2015 and 2022 internet traffic increased with 600 % and data centre workloads with 340 %, still energy consumption rose less than 100 % (IEA, 2023). Due to the extreme nature of these historical trends, it is difficult to say which force will be steering the development the coming decades. To address this issue, two versions of the intensified ICT use scenario are constructed: one case with frozen efficiency, and one case which incorporates comprehensive efficiency gains, hereby called the *intensified efficient ICT use scenario*.

As emerging technologies have the potential to change both the amount and the impact of ICT products and services, diffusion of some emerging technologies are modelled in the scenarios in this study. Freitag et al. (2021) have mapped out trends in ICT which can come to affect the emissions tied to the sector. Beyond blockchain, which is not included in the scope of this study, the authors discussed AI and IoT. As these emerging technologies already have entered the consumer sphere, for example through ChatGPT and Phillips Hue light bulbs, they are considered as driving forces in the scenarios. Another emerging technology is XR (see for example Jakopin et al. (2023)), which is also modelled in the foreground system. Apart from implementation of new technologies, the use patterns of ICT can also change. Therefore, changes in the type of content which is consumed, as well as the time spent on ICT are modelled in the scenarios. Table 4.1 shows a description of the three developed scenarios, which are further elaborated in the sections below.

Table 4.1: Description of the three constructed scenarios.

Scenario	Description
Intensified ICT use	Increased consumption of IoT and XR devices
	Large scale implementation of AI in consumer use cases
	Increased use time of ICT
	Larger demand for high resolution and video-style content
Intensified efficient ICT use	Same consumption level as in the intensified ICT use, but assuming comprehensive efficiency gains
Multi-functional ICT	Substitution of traditional user devices with XR devices
	No further implementation of AI and IoT
	Similar use time of ICT as today
	Similar use cases of ICT as today

4.2.1 Intensified ICT use

To emphasise the wide range of possible outcomes, the intensified ICT use scenario builds on a comprehensive implementation of the previously mentioned emerging technologies. Starting with AI, the modelled expansion can be motivated by the rise of AI services such as ChatGPT, Gemini, Siri, and Google Assistant. A recent study indicated that around 30% of Swedes had used some form of AI tool the past year (The Swedish Internet Foundation, 2023). Among Swedes between the ages 18 and 34, the corresponding number was 60%. These figures indicate the potential for widespread adoption of the technology. The interest in AI is also present within academia and industry: the past years, in Europe, patents connected to AI have increased at higher rates compared to patents in general (Williams et al., 2023). Freitag et al. (2021) state that emissions tied to data centres is likely to be the primary impact from AI implementation on emissions from ICT. In this study, the effects of increased AI use are therefore solely modelled for the data centre category. This simplification is also motivated by the fact that current user devices have shown to suffice for usage of many AI services.

Regarding IoT, a study by The Swedish Internet Foundation (2021) found that around 70% of Swedes have an internet-connected device in their home in addition to smartphones, computers, and tablets. The study also highlighted that these devices are more commonly found in high-income households than in low-income households. Moreover, fewer retired people had such devices when compared to the average. Due to expected decreases in product costs (see for example Statista (2023b)) and demographic changes, an increase in the use of IoT devices is therefore assumed in the intensified ICT use scenario. Freitag et al. (2021) stressed that emissions tied to user devices and networks are likely to be the primary emission impacts from IoT. However, to reduce the complexity of the model, only the effects of the manufacturing of user devices are considered for this technology.

In this study, beyond the increase in AI and IoT use, an increased use time is modelled for the intensified ICT use scenario. As the use time is an integral aspect of ICT consumption its effects are modelled for all three ICT categories. The modelling of use time increases is motivated by technological and demographic changes. Swedes in ages between 15 and 24 spent around 7 hours consuming digital media (excluding direct radio) per day in 2019, compared to the 5-hour national average (based on Nordicom, University of Gothenburg (2020)).

In light of the past years' increase in virtual reality (VR) headset sales (Statista, 2024), a large-scale introduction of XR headsets is also modelled. As XR devices have the potential to leave their user susceptible to their surroundings while still being immersed in the product, they might further drive increases in ICT use time. The hands-free functionality of some XR devices could further support this trend. In an advertisement for the XR device Apple vision pro, the possibility for users to interact with their environment was explicitly stated:

> ”Foundational to Apple vision pro is that you're not isolated from other people. When someone else is in the room, you can see them and they can see you” (Apple, 2023c).

As both demographic changes and the introduction of XR might increase the ICT use time, it is set to 10 hours of ICT use outside work per person and day in 2050. The 10-hour mark is chosen as it lies close to the time available per day outside work and sleep.

Finally, motivated by projections from Jakopin et al. (2023), an increase in higher resolution video and video-style content is also modelled for this scenario. The effects of this increase are only modelled for the networks, to maintain sufficient simplicity.

4.2.2 Multi-functional ICT

As the multi-functional ICT case largely represents current ICT use, no increase in use time nor AI and IoT implementation is modelled. However, supported by the previously mentioned increase in VR headset sales, XR devices are modelled to replace traditional user devices such as smartphones, desktops, and televisions. This is motivated by the multi-functionality of XR headsets and represents a provision of the same ICT functions with a smaller resource use. To summarise the conceptual scenario development, Table 4.2 shows the discussed trends and the categories for which they are modelled.

Table 4.2: Trends which are considered in the scenario design and the ICT categories they are modelled to affect.

Trend	Affected categories
AI implementation	Data centres
IoT implementation	User devices
XR implementation	User devices
Increased use time	User devices, Data centres, Networks
Increased video content and resolution	Networks

4.3 Quantitative scenario design

In the following sections, the proxy analysis together with the conceptual scenario design are used to quantify the foreground system scenarios. The sections are structured around the three analysed ICT categories: user devices, networks, and data centres. Detailed descriptions including sources, complementary data, and the results from the foreground system modelling are presented in Appendix A.

4.3.1 User devices

Of the trends mapped out in the scenario design, three are relevant for the modelling of user devices: implementation of IoT and XR, and an increased use time. For the intensified ICT use scenario, a high penetration rate for all user device types is assumed to get an upper bound on the user device sales. The number of purchases of traditional user devices are kept constant for all years. This is motivated by estimates indicating large penetration rates for traditional consumer electronics in Sweden, over 90 % for both smartphones (Statista, 2023a) and laptops (AudienceProject, 2018). Considering the sustained, high usage of traditional devices, a penetration rate of only 50% for XR devices is assumed. Conversely, the use of IoT devices is modelled to increase significantly, as they do not require any active user input. Representing a 100 % penetration rate of IoT devices, all households are modelled to have one active smart speaker and security camera in 2050. For wearables, the number of purchases in 2050 is assumed to be similar to the current sales of smartphones.

For the multi-functional ICT case, no change relative to the baseline year in the number of purchases of IoT devices per capita is assumed. However, traditional user devices are modelled to be substituted with XR devices. To set the scale of the substitution, historical figures on the smartphone's substitution of digital cameras are used as a reference. CIPA's digital camera sales decreased with more than 90 % between 2010 and 2020 (CIPA, 2023). Simultaneously, global smartphone sales grew with 350 % (Gartner, 2023), achieving a 96 % penetration rate in 2020 (Statista, 2023a). Building on these figures, the substitution is assumed to decrease the number of purchases of traditional devices to 10 % of their 2020 value. A linear function is assumed for quantifying the purchases in the years between the baseline year and 2050.

The use time is adjusted in line with the conceptual scenarios. To get an estimate of the time spent in the baseline year, the use time per product is multiplied with the number of active products, and then divided by the Swedish population. The values for the use time per product are taken from various sources, but most notably from Urban et al. (2021). The calculations yield a use time of around 6 hours per day and capita, which is in line with the media use estimates from Nordicom, University of Gothenburg (2020). Note that no direct comparison between these two figures can be made, as the analysed products included in this study can be used for other activities than media consumption. Moreover, the time reported by Nordicom, University of Gothenburg includes media consumption on devices which are out of scope for this study, for example radios and newspapers. Nevertheless, the similarities indicate that the calculation yields reasonable results.

Table 4.3 summarises the use time per capita for the baseline year and 2050. Note that customer-premises equipment, security cameras, and smart speakers are excluded from the use time estimates, as they do not necessarily require active user input. As PC monitors are often used together with computers, they are not accounted for to avoid double-counting. Lastly, due to lack of data, the use time of wearables is not included. For these devices, the UEC is considered to be constant.

To account for the reduction of the active stock in the multi-functional ICT scenario, the use time of XR devices is scaled with a factor to keep the average total use time per capita constant. For the intensified use scenario, the XR headset use time is scaled to increase linearly, so that the 10-hour total average use time is reached in 2050. The increased use time per XR headset is then translated into a corresponding increase of the UEC, thereby changing the total user device energy consumption.

Table 4.3: Average use time per capita and device for the baseline year and the constructed scenarios. Only devices that require active user input have been considered.

Product	Use time in 2020 [h/day]	Use time in 2050 [h/day] intensified ICT use	Use time in 2050 [h/day] multi-functional ICT
Smartphone	3.5	3.5	0.5
Tablet	0.5	0.6	0.2
Laptop	0.7	0.7	0.1
Desktop	0.2	0.2	0.03
PC monitor	-	-	-
Customer-premises equipment	-	-	-
XR headset	0.02	3.8	5.0
Security camera	-	-	-
Smart speaker	-	-	-
Wearable	-	-	-
Television	1.3	1.3	0.3
TOTAL	**6.1**	**10**	**6.1**

Lastly, adjustments for the intensified efficient ICT scenario are made. Urban et al. (2021) observed a reduction of the unit energy consumption from 78 kW h per year to 53 kW h per year between 2006 and 2020. In the efficiency scenario, it is assumed that the historical trend will continue, with a reduction of $1 - \left(\frac{53\,\mathrm{kW\,h}}{78\,\mathrm{kW\,h}}\right)^{1/(2020-2006)} \approx 3\,\%$ per year. No efficiency gains in the manufacturing of the user devices are modelled in the foreground system. Instead, the emission reductions present in the background system, which result in reduced emissions from manufacturing, are considered to be sufficient.

4.3.2 Networks

Based on the conceptual scenario development, the changes in the consumed content and the use time are regarded in the modelling of the networks. For the multi-functional ICT scenario, the use cases and the use time are assumed to stay constant. Hence, the network energy consumption is assumed to stay at the baseline value. In the intensified ICT use scenario, a higher use time as well as a higher data intensity is included. The current and future data intensity for different use cases are modelled based on a study by Jakopin et al. (2023).

Calculating the change in data traffic requires the use times for different media forms, which are retrieved from Nordicom, University of Gothenburg (2020) for the baseline year. The use time increase in the intensified ICT use scenario is exclusively allocated to the video use case, as the additional time is assumed to be spent on XR devices. The assumptions made for the baseline year and the intensified ICT use scenario are summarised in Table 4.4.

Table 4.4: Assumptions regarding the use time per day and capita and the data traffic requirements for different use cases. The table shows both the values for the baseline year, 2020, and the values for the intensified ICT use scenario in 2050.

	2020		**2050**	
Use case	**Use time** [h]	**Data intensity** [GB/h]	**Use time** [h]	**Data intensity** [GB/h]
Video	1.9	2	5.7	10
Social media	0.9	1	0.9	3
Other (digital sound and text media)	1.8	1	1.8	1

By multiplying the use time and the data intensity given in Table 4.4, the total data traffic per day and capita can be calculated. The data traffic is estimated to 6 GB per day and capita in 2020, and 61 GB per day and capita in 2050 for the intensified ICT use scenario. Assuming frozen efficiency and a proportional relation between data traffic and network energy use, this yields a network energy consumption of $380\,\mathrm{GW\,h} \times \frac{61\,\mathrm{GB}}{6\,\mathrm{GB}} \approx 3.8\,\mathrm{TW\,h}$ in 2050 for the intensified ICT use. To model the years in between, the data intensity is assumed to increase linearly.

The efficiency gains in the intensified efficient ICT use scenario are modelled based on changes in the energy consumption per transmitted data. However, first the electricity intensity for the baseline year has to be estimated. This can be done by dividing the total network energy use with the total data traffic. Building on the aforementioned figures, the electricity intensity is estimated to

$$\frac{380\,\mathrm{GW\,h}}{6\,\mathrm{GB/(capita\ and\ day)} \cdot 10.35 \times 10^6\ \mathrm{inhabitants} \cdot 365\ \mathrm{days}} \approx 0.02\,\mathrm{kW\,h/GB}. \tag{4.1}$$

This value is in line with estimates from Pihkola et al. (2018), which stated that Finnish mobile networks could consume less than 0.1 kW h/GB in 2020.

Improvements in the electricity intensity are modelled based on an article by Björnson and Larsson (2018), in which the boundaries of wireless network efficiency were investigated. The authors suggested a practical limit of a few Tbit per Joule. Assuming 5 Tbit/J, this would correspond to around $4 \times 10^{-10}\,\mathrm{kW\,h/GB}$. In the intensified efficient ICT use scenario, the energy requirements are modelled to decrease linearly from the baseline values to reach the proposed practical limit in 2050. Recalculating the intensified ICT use scenario with these assumptions yields a total network energy consumption of less than 10 kW h in 2050. This is a drastic decrease compared to the regular intensified ICT use scenario. Note that the study by Björnson and Larsson (2018) solely focused on wireless networks, and that no distinction is made between network types in this scenario. Still, the network type influences the energy consumption (see for example Pihkola et al. (2018)). The lack of distinction demonstrates the rough nature of these figures.

4.3.3 Data centres

In the following section, the scenario design of the data centre energy consumption is presented. A more detailed description of the model can be found in Appendix B. In the scenarios in this study, the data centres are affected by the stipulated AI implementation and the use time increase. As the multi-functional ICT scenario assumes both constant use time and no changes in use cases, the energy consumption is kept at the baseline year level for all years. For the intensified ICT use scenario, an increase in use time from six hours to ten hours would result in a proportional growth in data centre energy consumption, assuming similar use cases and zero efficiency gains. For the AI implementation, two extreme examples, related to two common consumer use cases, are used to illustrate possible effects of the technology.

The first example relates to video streaming, and what would happen if AI were implemented so that all consumer-related energy consumption would change in line with a transition from normal video streaming to only streaming AI generated videos. The relevance of this example is motivated by the development of Sora, openAI's text-to-video tool. To get an upper estimate, the inference energy needed for each frame is approximated with that of text-to-image AI tools. This is likely a large overestimation, as the video frames need modification rather than total regeneration. Using a frame rate of 25 fps, and an energy consumption per frame of 2.9 W h (Luccioni et al., 2023), this would result in an inference energy consumption of 260 kW h per hour of streamed video. According to estimates from the IEA (2020), normal video streaming requires around 4 W h of data centre energy per hour. If all consumer use cases would increase in line with the estimated values, it would result in an increase of $\frac{260\,\mathrm{kW\,h}}{4\,\mathrm{W\,h}} \approx 65\,000$ times. This would mean that the Swedish energy consumption from data centres would be in the range of ten thousand TW h. For comparison, the total Swedish electricity production was around 170 TW h in 2022 (Statistics Sweden, 2023). These assumptions can therefore be deemed unreasonable. However, it is worth noting that some researchers[1] think that AI could consume all energy on earth in a non-implausible worst-case scenario. Although this is not a sensible scenario to model, it illustrates the wide range of possible futures.

The second example, more suitable for modelling, investigates a trend where all energy consumption follows a similar transition as one from Google searches to AI-powered Google searches. A normal Google search requires about 0.3 W h, and an AI-powered search around 6.9 W h of energy, although higher estimates have also been reported (de Vries, 2023). Assuming that the energy consumption of

[1]Personal communication with Prof. Olle Häggström, Chalmers University of Technology.

all consumer applications would evolve in line with the difference between these search methods, the energy use would increase $\frac{6.9\,\mathrm{W\,h}}{0.3\,\mathrm{W\,h}} = 23$ times. To construct the energy use in 2050 for the intensified ICT use scenario, the second example is used. Combining this with the aforementioned increase in use time, and using the baseline energy consumption of 290 GW h, this yields an energy consumption of $290\,\mathrm{GW\,h} \times \frac{6.9\,\mathrm{W\,h}}{0.3\,\mathrm{W\,h}} \times \frac{10\,\mathrm{h}}{6\,\mathrm{h}} \approx 11\,\mathrm{TW\,h}$ for data centres in 2050. For the years between the baseline year and 2050, the use of AI is assumed to increase linearly. Note that this calculation assumes no efficiency gains. A description of the intensified efficient ICT scenario follows below.

For data centres, one frequently used energy use metric is the power usage effectiveness (PUE) (RISE, 2023), which is defined as

$$\mathrm{PUE} = \frac{\text{Total data centre energy consumption}}{\text{IT equipment energy consumption}} \tag{4.2}$$

(International Organization for Standardization, 2016). Beyond the IT equipment, the total energy consumption also includes the energy use from supporting systems, such as cooling and lightning. From the definition it is apparent that a PUE value of one represents a data centre where all energy is used by the IT equipment. In a survey by the Uptime Institute, the average annual PUE for the respondents' largest data centre was stocktaken. The results indicated an average PUE of 1.55 (Davis et al., 2022). The data centre Boden Type Data Center, funded by the EU, has achieved a close to perfect PUE of 1.02 (CORDIS, European Commission, 2022). As this PUE value has been shown practically viable, an average value of 1.02 is assumed to be accomplished in 2050 for the intensified efficient ICT use scenario.

Beyond the PUE value, the efficiency of the IT equipment also has to be considered. Computing represents around 40 % of the data centre electricity consumption (IEA, 2024), with the remainder mostly being used for surrounding infrastructure such as cooling (Masanet et al., 2020). Therefore, the development in computing efficiency is used to estimate all IT equipment energy use. Prieto et al. (2024) have studied the evolution of energy efficiency, EE, in computations in high-performance computers between 2008 and 2023, and propose the following relation for the highest performing computer on the Green500 list

$$EE = 3 \cdot 10^{-273} \cdot e^{0.3122 \cdot \mathrm{year}}\ \mathrm{GFLOPS/W}. \tag{4.3}$$

The authors further state that values connected to high-performance computers are widely applicable, as the magnitudes of the efficiency of lower-performance devices lie in similar ranges. However, they also note that the established relation should only be used for short-term projections, as the technological landscape changes rapidly. In spite of this dissuasion, the results are used to model long-term energy efficiency, justified by the explorative aim of the study. Using the formulas presented by Prieto et al., the Landauer limit would be reached around 2080 if the aforementioned trend continues. The Landauer limit is a proposed theoretical limit for the energy requirements of computations, which is determined using the second law of thermodynamics and the Boltzmann entropy formula (Prieto et al., 2024). It states that the minimum energy loss from erasing one bit of information is $3 \cdot 10^{-21}$ J (Prieto et al., 2024). This erasure can, for example, be an irreversible computation. As the Landauer limit is not reached within the time frame of the scenarios, the used estimate does not surpass Landauer's theory of the physics governing the energy consumption of computations.

To represent energy efficiency improvements, the PUE values are modelled to decrease linearly, reaching 1.02 in 2050. Simultaneously, the IT equipment energy consumption is assumed to follow the relation in equation 4.3, meaning a reduction of the IT equipment energy consumption to $\frac{3 \cdot 10^{-273} \cdot e^{0.3122 \cdot 2020} \text{ GFLOPS/W}}{3 \cdot 10^{-273} \cdot e^{0.3122 \cdot 2050} \text{ GFLOPS/W}} < 0.01\,\%$ of the 2020 value in 2050.

4.4 Discussion

In summary, three different scenarios are developed in this study: intensified ICT use, intensified efficient ICT use, and multi-functional ICT. The scenarios are based on information about emerging technologies, estimates of future material and energy consumption through proxies, and historical trend analysis. As is apparent from the results above, a simple framework was used for the scenario design. Considering the vast effects technological revolutions, like the Industrial Revolution, can have, it is apparent that the range of possible futures could be much wider than what is depicted in this study. To further elaborate the scenarios, future studies can use other design frameworks. For example, Börjeson et al. (2006) mentions participatory approaches such as the Delphi method, in which expert opinions act as the main input. Other similar approaches include workshops and surveys.

Another method which can be used for designing scenarios is the 2×2 matrix technique, which has been described by Rhydderch (2017). Here, the two factors with the largest uncertainties and impacts are selected and placed on two orthogonal axes. The resulting four quadrants then serve as four distinct scenarios. This facilitates the creation of both vivid and differentiated scenarios. Due to the method's relative simplicity, it was tested for this project. For example, axes concerning the data traffic use, the number of user devices, and the energy intensity per data traffic were analysed. However, the method was difficult to apply due to the sector's fragmentation. As is apparent from earlier sections, the climate impact of the ICT sector is estimated using different proxies for the three ICT categories. The restriction tied to choosing only a few factors subsequently led to scenarios that were either too narrow or too abstract.

Another important methodological choice is the use of proxies. Using proxies for the behaviour of a rapidly changing technology, like ICT, is in itself precarious. As the function of these technologies might change in the future, for example due to a shift towards more computation focus in data centres due to AI, the proxies might become so outdated that no adjustment of the assumed parameters yields a meaningful model. To safeguard against the issues mentioned above, a wide range of foreground systems are constructed. Finally, fully excluding long-term projections makes action for climate targets significantly more challenging. Therefore, although the simplifications made may be considered enough to discredit the analysis, its contribution in terms of providing a range of possible outcomes was deemed greater than the risk of creating factoids.

The use of proxies was especially difficult for the data centre energy use, for which no suitable high-level approach was found. Moreover, the energy use in the high consumption scenarios were based on an assumption of uniform energy increases across all use cases. A model differentiated by use case would increase the robustness of the analysis. However, data gaps and lack of consensus around suitable proxies limit the possibilities of effectively modelling future data centre energy use. Consequently, a discussion about data availability and quality is warranted. Among other issues, Mytton and Ashtine (2022) mention that private sources are commonly used to analyse data centre energy consumption. This undermines the possibilities of reviewing and recreating studies. Moreover, the authors observed that there is a large reliance on specific authors and organisations, such as Koomey, Andrae, and Cisco, which fittingly also have been used for this study. Additionally, many frequently cited authors in the field have conflicts of interest. For example, Andrae is employed at Huawei, Malmodin at Ericsson, and Koomey has received modest research funding from Sony Interactive Entertainment. In summary, further research aiming to establish open and up-to-date data is needed.

The issue of data availability is further exacerbated by the country-level focus of this study. As is apparent from the scenario design, global averages are continually used to estimate trends on national level, due to a shortage of regional data. In addition, the average global emission intensity is used to estimate the impact of networks and data centres, even though data centre energy consumption is unevenly distributed around the world. For example, in an allocation made by Malmodin et al. (2024), more than a third of global electricity use from data centres was assumed to be consumed in the US.

Lastly, the use of linear interpolation between the baseline year and 2050 can be questioned. Admittedly, the function is used to enable a simple model. However, in future works, it might be more suitable to implement product-specific curves. One starting point could be S-shaped functions, which, as previously mentioned, capture a common diffusion pattern of new technologies (Grübler, 1998).

5

Scenario analysis of Swedish ICT

In the following sections, the modelled emission pathways are presented and compared to the total consumption-based emissions in Sweden. Then, the modelled energy consumption and the results from the sensitivity analysis are introduced and discussed. Detailed results in table format can be found in Appendix D.

5.1 Emission pathways

The modelled pathways for Swedish consumption-based ICT emissions are shown in Figure 5.1. The emissions in the baseline year are estimated to 0.13 ton CO_2eq per capita and year. In comparison to the total Swedish consumption-based emissions, which were around 9.8 ton carbon dioxide equivalents in 2019 (Morfeldt et al., 2023), ICT represents approximately 1.3 %. A similar ratio between ICT emissions and total emissions has been found on a global level (Malmodin et al., 2024), which could indicate that the model is accurately calibrated. Note that the estimate by Malmodin et al. includes both business and private use. Nevertheless, the study was used as a reference point due to the lack of literature on consumption-based emissions from ICT.

From the figure it is apparent that all scenarios result in lower emissions in 2050 compared to the baseline year. The multi-functional ICT case decreases most, reaching 0.02 ton CO_2eq per capita in 2050. The intensified efficient ICT use scenario results in similar reductions, yielding 0.03 ton CO_2eq per capita in 2050. Contrary to the other pathways, the intensified ICT use scenario initially increases emissions, followed by a reduction, resulting in 0.08 CO_2eq per capita in 2050. This corresponds to a decrease of around 40 % compared to the baseline year.

To put the development into a context, the pathways can be compared with scenarios aiming to quantify budgets for consumption-based emissions per capita. It is however important to note that these types of estimates vary depending on how emissions are allocated, which target is chosen, and much more. Ala-Mantila et al. (2023) constructed emission budgets based on the SSP1-1.9, while assuming an equal share of emissions per capita. Based on these premises, the authors proposed an emission budget of around one ton carbon dioxide equivalents per capita and year in 2050. Using this figure as an upper emission limit results in a larger share of emissions attributed to ICT in 2050 when compared to the baseline year. In Ta-

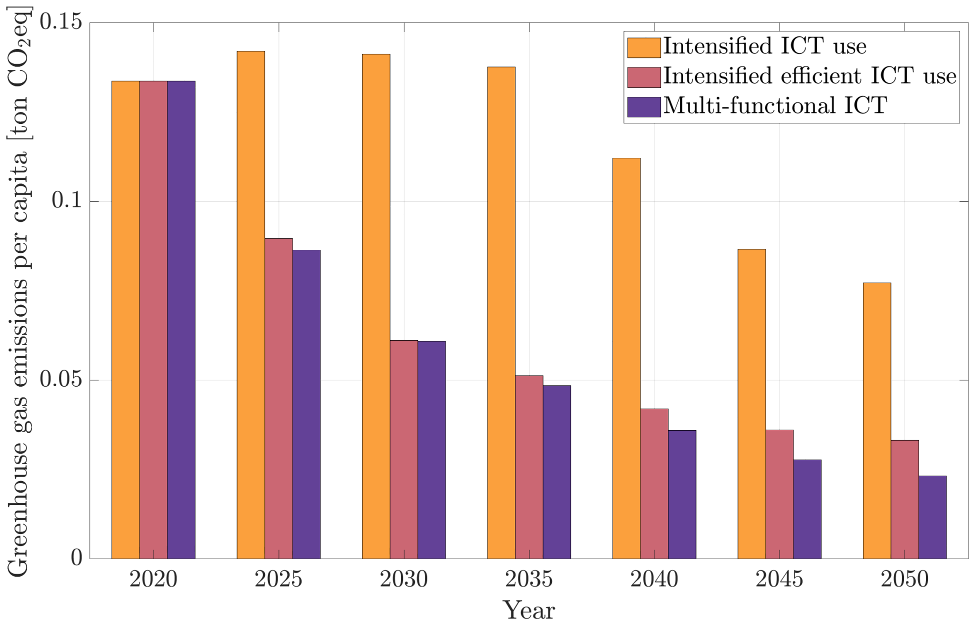

Figure 5.1: Emission pathways for Swedish consumption-based emissions from ICT. The figure displays the three modelled scenarios.

ble 5.1, an overview of the development of ICT's share of total consumption-based emissions is shown. Remember that the share in the baseline year is estimated to 1.3 %.

To further investigate the pathways' accordance with climate targets, the results can be compared with findings from Morfeldt et al. (2023), which studied the future of consumption-based emissions in Sweden. The authors found that advanced technology along with behavioural changes could result in per capita emissions around 2.7 to 4.8 ton CO_2eq in 2045. This range partly aligns with the proposals made for the Swedish net-zero consumption-based emission target, which are discussed in the article. When using the two low-emission scenarios modelled in this study and comparing them to the lower end of the range provided by Morfeldt et al., the share of ICT emissions is constant or decreases in relation to the baseline year.

Table 5.1: The share of ICT emissions compared to total emission budgets. The values for the total emission budgets are derived from Morfeldt et al. (2023) and Ala-Mantila et al. (2023) and are compared to the scenario estimates for the years 2045 and 2050 respectively.

Scenario	Share of emission budget for total of 2.7 ton CO_2eq	Share of emission budget for total of 1 ton CO_2eq
Intensified ICT use	3.2 %	7.7 %
Intensified efficient ICT use	1.3 %	3.3 %
Multi-functional ICT	1.0 %	2.3 %

To present the drivers of ICT-related emissions, Figure 5.2 depicts the share of emissions allocated to each category: user devices, data centres, and networks. The figure shows that user devices accounted a majority of the emissions in the baseline year. For the multi-functional ICT and the intensified efficient ICT use scenarios, the share of emissions from user device production increases. This is primarily due to the comprehensive reductions in emission intensity for the global electricity mix, as well as the stalled or decreasing energy use. Contrary to the other pathways, data centres represent a notable share of the total ICT emissions in 2050 for the intensified ICT use scenario. This is due to the drastic increase in energy use from data centres, which also is the driver of the initial emission increase in this scenario. In absolute terms, the embodied emissions from user devices are quite similar in all three scenarios.

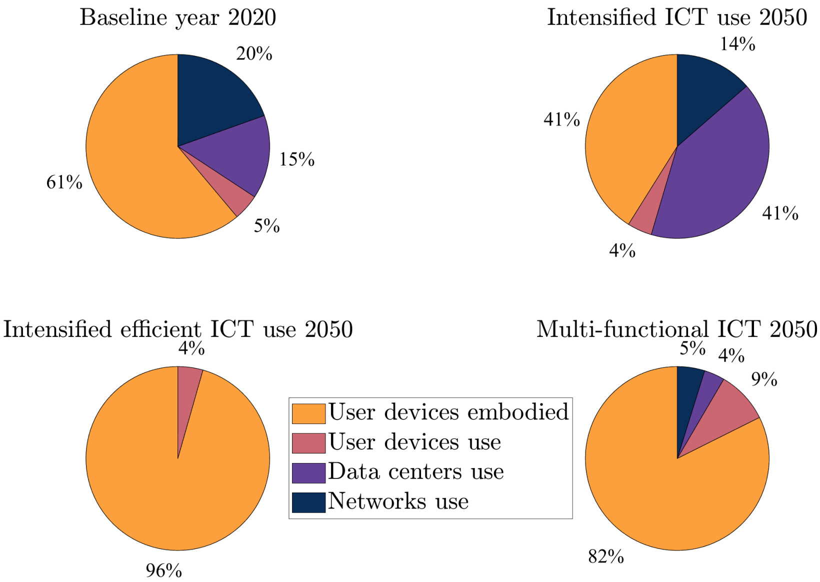

Figure 5.2: Percentage of Swedish consumption-based ICT emissions allocated to the four investigated life cycle phases and categories.

According to global estimates by Malmodin et al. (2024), the user devices' use phase represented around 30 % of total ICT emissions in 2020. In contrast, the same life cycle phase represents a maximum of roughly 10 % of emissions across all scenarios and years modelled in this study. This is a consequence of the low emission intensity of Swedish electricity.

5.2 Energy consumption

The modelled energy consumption connected to the use phase is shown in Figure 5.3. For the baseline year and the multi-functional ICT scenario the energy consumption is around 2.1 TW h. The intensified ICT use scenario yields an energy consumption of 17 TW h in 2050, compared to only 960 GW h for the intensified efficient ICT use scenario.

The total Swedish electricity use was around 134 TW h in 2020 (Swedish Energy Agency, 2023), meaning that the ICT energy use in 2020 would correspond to less than 2 % of the total use. Note, however, that the network and data centre energy use is not only occurring within the Swedish territory. To further contextualise the results, they can be compared to scenarios for the total Swedish electricity use made by the Swedish Energy Agency (2023). In their high electrification scenario, the agency modelled that Swedish electricity use will rise to 349 TW h in 2050. This is more than double that of the 2020 value. For the same scenario, the upper bound of the total data centre electricity use in 2050 was assumed to be around ten times that of their estimated consumption of 2 TW h in 2020. Comparably, the data centre energy use was modelled to increase more than thirty times for the intensified ICT use scenario analysed in this study. For the low electrification scenario, the Swedish Energy Agency projects a fivefold data centre electricity consumption in 2050 compared to 2020. The intensified efficient ICT use scenario results in a data centre energy use of less than 1 % in 2050 when compared to this project's baseline year estimate for the data centre energy consumption.

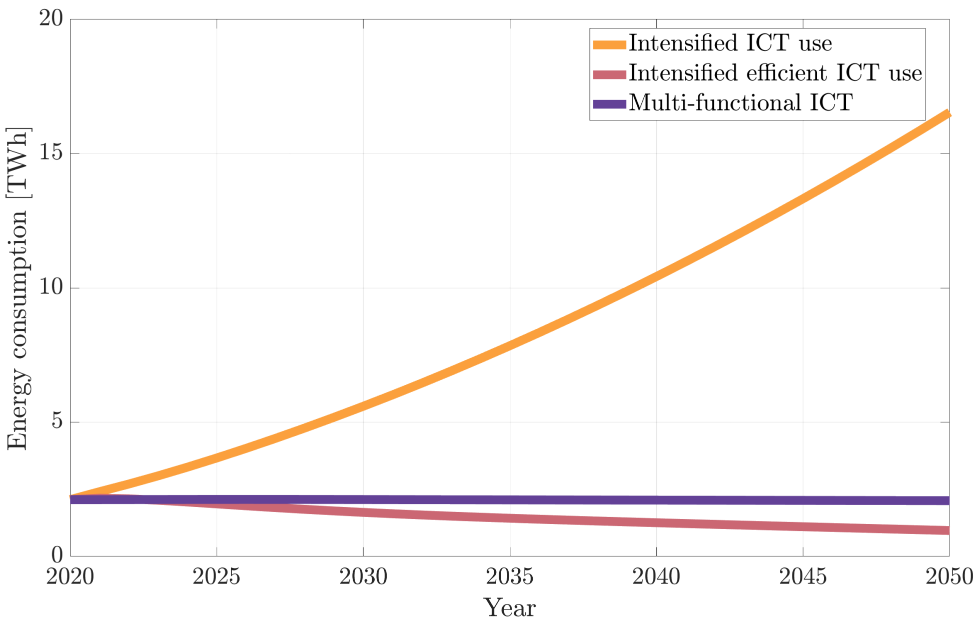

Figure 5.3: Modelled energy consumption from the use phase of data centres, networks, and user devices for the three scenarios.

5.3 Sensitivity analysis

The networks and data centres represent a sizeable share of the emissions in the baseline year, around 35 %. As the energy use of data centres in the baseline year is derived from the network energy consumption, the model's sensitivity to this parameter is analysed. To test the sensitivity, the back-of-the-envelope estimate of 510 GW h for the baseline year network energy consumption is used. This value was derived in the methods (section 3.2.4) and was used to corroborate the baseline year value. This approximately 25 % increase in network and data centre energy use results in a maximum increase of emissions across all scenarios and years of 21 %, while the average increase is 10 %. The latter is in line with linear sensitivity, pointing towards moderate model sensitivity to this parameter. Details on the results from the sensitivity analysis can be found in Appendix D.

Another key uncertainty lies in the extrapolation of historical efficiency gains for the user devices and the IT energy consumption in data centres. For example, changing the UEC reduction percentage from 3 % to 2 % per year yields a 25 % increase of the user device energy consumption in 2050. Issues with extrapolations are well known within the field of future-oriented ICT studies, as said by Mytton and Ashtine (2022):

> ”(...) extrapolation erodes statistical confidence (...)”.

Lastly, investigating the other analysed background system pathways reveals the importance of the choice of the background system scenario (for details see Appendix D). For example, the SSP5-Base scenario gives drastically increasing emissions for the intensified ICT use scenario, contrary to the aforementioned results. For the status-quo background system, similar increases are seen. Moreover, the multi-functional ICT and the intensified efficient ICT use scenarios only show modest decreases in emissions for both the status-quo background system and for the SSP5-Base case.

5.4 Discussion

To summarise, the constructed pathways illustrate that ICT emissions likely represent a relatively small share of consumption-based emissions in Sweden. Additionally, all the modelled scenarios result in emission reductions when using the SSP2-NDC background system. Due to large uncertainties, it is difficult to assess the pathways’ alignment with climate targets. However, the analysis points towards a decreasing or constant share of ICT emissions for the multi-functional ICT and the intensified efficient ICT use scenarios, when compared to the emission trajectories studied by Morfeldt et al. (2023). Under an assumption that the share of emissions related to all sectors will remain constant, the results would indicate that these scenarios might be sufficient to stay in line with the proposed targets.

When analysing future emissions from ICT, it is worth noting that a higher ICT use might result in decreased emissions elsewhere. As the intensified ICT use scenario assumes extreme use times, this scenario likely also entails reducing time spent on other activities. One example of these avoided emissions, or substitutions, related to ICT is virtual conferences, which according to Tao et al. (2021) have the potential to reduce the climate impact significantly when compared to their in-person analogue. Although avoided emissions are out of scope for this study, it is important to highlight that if more functions progressively are included in the ICT sphere, rising emissions from ICT do not necessarily correspond to non-compliance with nation-wide climate targets stipulating decreasing emissions. On the other hand, as mentioned by Bieser et al. (2023), Court and Sorrell (2020), and Freitag et al. (2021), imperfect substitution and rebound effects might reduce the benefits of this shift.

The results also show that the background system is the biggest determinant of the emission levels. Although the consumption level influences the outcome, changes in the background system have more drastic effects. The importance of the background system is apparent from the results, naturally, the emission intensity needs to decrease for scenarios with higher consumption levels to result in a reduction of emissions. It is further important to note that the interaction between the consumption patterns and increasing efficiencies in the background and foreground systems is not studied in this work. In light of Jevons paradox, which states that increased efficiency tends to drive increases in resource use (York, 2006), the exclusion of this interaction might have considerable impact on the results. Although the causal relationship between efficiency gains and rising resource use within ICT has not yet been determined, Freitag et al. (2021) highlight that there are examples of historical patterns in the sector which resemble those described by Jevons paradox.

The status-quo background system also suggests that a low consumption level, as it is interpreted in this thesis, is not enough to reduce emissions significantly. Evidently, the modelled shift to more multi-functional devices is not a sufficient measure. To further study the impact of consumption patterns, future works should incorporate more drastic low consumption scenarios. One interesting field of study would be an increased lifetime of user devices, as embodied emissions account for a majority of the emissions in both the baseline year and the two low-emission scenarios. This is especially relevant as the user devices' use phase emissions account for a smaller share of Swedish consumption-based ICT emissions when compared to findings on a global level (cf. Malmodin et al. (2024)), due to the low emission intensity of Swedish electricity. Similar results have been found by Istrate et al. (2024), which recommend directing focus towards embodied emissions in countries with low-emission electricity mixes. The relevance of studying lifetime extension can further be motivated by the decrease in the median lifetime of phones following the transition from feature phones to smartphones, observed by Zhilyaev et al. (2021). However, for the average global consumer, the effect of electronic device lifetime extension on the climate impact of digital content consumption has been shown to be rather modest (Istrate et al., 2024).

Contrary to the emission pathways, the energy consumption scenarios display more extreme behaviours, especially when compared to the scenarios constructed by the Swedish Energy Agency (2023). Due to the explorative nature of the thesis, the investigated scenarios are not to be viewed as projections of future energy use. The used model does not, for example, provide any indication on whether the energy consumption is feasible from an economic standpoint. For example, de Vries (2023) argues that both the cost and the time frame of adoption of AI could counteract scenarios leading to extreme energy use. On the other hand, Sam Altman, CEO of OpenAI, has stated that future AI is reliant on extensive energy development, saying

"There's no way to get there without a breakthrough" (Dastin, 2024).

Similarly, the model does not account for potential changes in the rate of efficiency gains. As highlighted by Freitag et al. (2021), some experts in the field believe that the improvements in efficiency will not continue. However, in case of reduced emission intensities for energy use, an increase in energy consumption must not necessarily pose as a problem for reaching climate targets. Still, the IPCC has stated that demand-side actions that reduce energy consumption may decrease the costs of climate change mitigation (Creutzig et al., 2022).

Lastly, the intensified efficient ICT use scenario may have implications beyond the aspects of ICT considered in this study. As the embodied emissions from networks and data centres are not included in the model, the drawbacks of substituting existing equipment with newer, more efficient versions, are not included. Incorporation of these life cycle phases would likely increase the relative emissions in comparison to the two other scenarios. However, the substitution might still be worthwhile: Andrae (2023) claims that large network equipment should not be reused due to the potential of efficiency improvements.

6
Conclusion

This study set out to investigate how Swedish consumption-based emissions from ICT can be reduced. To achieve the aim, two method-development research questions were also studied. The first question regards the development of proxies for the future material and energy consumption of the sector. The second question concerns what scenarios are relevant for studying future reductions of emissions from ICT.

Regarding the first question, the research shows that both the use and choice of proxies are highly disputed within the ICT community. Despite evident drawbacks, data traffic is deemed to be the most suitable, currently available, proxy for estimating consumption-based energy use from networks. Contrary to the networks, no suitable proxy was found for evaluating the energy use from data centres. This was partly due to difficulties with translating proxies suggested in previous research into consumption of end user services. For the embodied emissions of user devices, the availability of product-differentiated data, and the presence of well-established stock-flow models, motivates the use of bottom-up approaches rather than high-level estimates. For all ICT categories, the use time can help capture effects that changes in consumption patterns have on use phase emissions. A challenge in proxy development for ICT is the lack of public and up-to-date data within the field. Therefore, it is recommended that future works focus on establishing open data to inform more detailed models on energy use and emissions related to ICT services.

The scenario development resulted in three foreground system pathways, one with intensified ICT use, one with a shift towards multi-functional ICT devices, and lastly, one with intensified but efficient ICT use. By constructing scenarios based on two diametric consumption intensities, the explorative aim of the study was captured. Many other conceptual scenario design methods are present and could be used in future research to study other aspects of consumption-based ICT emissions. Due to difficulties with applying the 2×2 matrix approach, participatory methods might be a good starting point.

Returning to the overarching aim, the investigated pathways indicate that ICT likely accounts for a small share of Swedish consumption-based emissions, both currently and in the future. The background system, meaning the emission intensity of electricity and manufacturing of user devices, influenced the emission levels more than the modelled level of consumption. However, as the study does not investigate all possible measures for reducing consumption, such as lifetime extension of user devices, further research is required to increase the robustness of this conclusion. The results also suggest that comprehensive efficiency gains, especially in data centres and networks, can yield similar emission reductions as lower levels of consumption. Note, however, that the modelling of the data centre energy use still requires additional analysis, as the used method is built on large generalisations across different use cases. It is therefore recommended that future research directs extra attention towards developing methods for estimating data centre energy use from a consumption-based perspective.

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A

Appendix

Foreground system model

Table A.1: Unit energy consumption (UEC) with a description of the used assumptions. All values are based on the study by Urban et al. (2021).

Product	UEC [kWh/year]	Assumption
Smartphone	4.5	
Tablet	6.1	
Laptop	36	Scaled with 2017 values to exclude work hours
Desktop	220	Scaled with 2017 values to exclude work hours
PC monitor	62	Scaled with 2017 values to exclude work hours
CPE	102	Used the UEC for all network devices
XR-headset	22	
Security camera	31	
Smart speaker	22	
Wearable	0.50	
Television	61	Scaled with use time reported by Davidsson and Findahl (2016)

Table A.2: Use time per product with a description of governing assumptions.

Product	Use time [h/day]	Source & Assumption
Smartphone	3.2	Average use per capita from Telenor (2019) divided by active stock in 2020 and multiplied with total population (10.35 million)
Tablet	1.6	Assumed half the use time of smartphone due to lack of data.
Laptop	2.0	(Urban et al., 2017) used only the high active time
Desktop	2.4	(Urban et al., 2017) used only the high active time
XR-headset	1.5	(Urban et al., 2021) use per year divided by 365
Television	2.0	(Davidsson & Findahl, 2016) Mistake: This value does not account for the difference between the use time per product and the use time per person (which is what is given in the source)

Table A.3: Wave classification for products.

Product	Wave classification
Smartphone	2nd
Tablet	2nd
Laptop	2nd
Desktop	1st
PC monitor	1st
CPE	1st
XR-headset	2nd
Security camera	2nd
Smart speaker	2nd
Wearable	2nd
Television	1st

Table A.4: Sales of user devices in the baseline year.

Product	Sales 2020	Source and assumptions
Smartphone	3 100 000	(Statista, 2024) Used the volume for 2020 of the market smartphones with region Sweden
Tablet	600 000	(Statista, 2024) Used the volume for 2020 of the market tablets with region Sweden
Laptop	500 000	(Statista, 2024) Used the volume for 2020 of the market laptops with region Sweden
Desktop	122 100	(Statista, 2024) Used the volume for 2020 of the market desktop PCs with region Sweden
PC monitor	500 000	(Statista, 2024) Used the volume for 2020 of the market PC Monitors & projectors with region Sweden
CPE	609 378	Multiplied the shipments of all network equipment reported in Urban et al. (2021) with the ratio of the Swedish and American population in 2020 (~ 0.00314)
XR-headset	44 550	(Statista, 2024) Used the volume for 2020 of the market VR-headsets with region Sweden
Security camera	98 848	Divided the number of users of internet connected home alarm systems between ages 16-85 from Statistics Sweden (2020) with the average number of people per household (2.2) and an assumed lifetime of 6 years.
Smart speaker	600 000	(Statista, 2024) Used the volume for 2020 of the market smart speakers with region Sweden
wearable	609 000	Used the number of users of ”smart watches, fitness watch, ... ”' from Statistics Sweden (2020) divided by an assumed lifetime of 3 years.
Television	800 000	(Statista, 2024) Used the volume for 2020 of the market televisions with region Sweden

Table A.5: The parameters used for the Weibull survival function, including sources.

Product	λ	κ	Source and assumption
Smartphone	3.53	1.83	Zhilyaev et al. (2021) used ”smartphone era” parameters
Tablet	5.18	0.88	Zhilyaev et al. (2021)
Laptop	7.50	4.59	Zhilyaev et al. (2021)
Desktop	6.60	1.97	Zhilyaev et al. (2021)
PC monitor	6.45	3.75	Kalmykova et al. (2015) used LCD value
CPE	6.45	3.75	Assumed same as PC monitor
XR-headset	3.53	1.83	Assumed same as smartphone
Security camera	6.45	3.75	Assumed same as PC monitor
Smart speaker	3.53	1.83	Assumed same as smartphone
Wearable	3.53	1.83	Assumed same as smartphone
Television	8.98	3.06	Kalmykova et al. (2015) used LCD value

Table A.6: Energy use in GW h from ICT due to Swedish consumption in the intensified ICT use scenario. Note that the values given do not include the energy for the manufacturing and transportation of user devices.

Category	2020	2025	2030	2035	2040	2045	2050
User devices	1440	1540	1670	1810	1940	2070	2200
Networks	380	650	1030	1520	2100	2790	3580
Data centres	290	1470	2280	4520	6380	8460	10760

Table A.7: Energy use in GW h from ICT due to Swedish consumption in the multi-functional ICT scenario. Note that the values given do not include the energy for the manufacturing and transportation of user devices.

ICT category	2020	2025	2030	2035	2040	2045	2050
User devices	1440	1450	1450	1440	1430	1420	1410
Networks	380	380	380	380	380	380	380
Data centres	290	290	290	290	290	290	290

Table A.8: Energy use in GW h from ICT due to Swedish consumption in the intensified efficient ICT use scenario. Note that the values given do not include the energy for the manufacturing and transportation of user devices.

ICT category	2020	2025	2030	2035	2040	2045	2050
User devices	1440	1350	1270	1190	1120	1040	960
Networks	380	320	250	190	130	60	10^{-5}
Data centres	290	290	110	30	10	2	0.6

Table A.9: Number of sales due to Swedish consumption for the intensified ICT use scenario.

Product	2020	2025	2030	2035	2040	2045	2050
Smartphone	3100000	3100000	3100000	3100000	3100000	3100000	3100000
Tablet	600000	600000	600000	600000	600000	600000	600000
Laptop	500000	500000	500000	500000	500000	500000	500000
Desktop	122100	122100	122100	122100	122100	122100	122100
PC monitor	500000	500000	500000	500000	500000	500000	500000
CPE	609377	609377	609377	609377	609377	609377	609377
XR-headset	44550	295458	546367	797275	1048183	1299092	1550000
Security camera	98848	224040	349232	474424	599616	724808	850000
Smart speaker	600000	733333	866666	1000000	1133333	1266666	1400000
Wearable	609000	1024166	1439333	1854500	2269666	2684833	3100000
Television	800000	800000	800000	800000	800000	800000	800000

Table A.10: Number of sales due to Swedish consumption for the multi-functional ICT scenario.

Product	2020	2025	2030	2035	2040	2045	2050
Smartphone	3100000	2635000	2170000	1705000	1240000	775000	310000
Tablet	600000	510000	420000	330000	240000	150000	60000
Laptop	500000	425000	350000	275000	200000	125000	50000
Desktop	122100	103785	85470	67155	48840	30525	12210
PC monitor	500000	425000	350000	275000	200000	125000	50000
CPE	609378	609378	609378	609378	609378	609378	609378
XR-headset	44550	553792	1063033	1572275	2081517	2590758	3100000
Security camera	98848	98848	98848	98848	98848	98848	98848
Smart speaker	600000	600000	600000	600000	600000	600000	600000
Wearable	609000	609000	609000	609000	609000	609000	609000
Television	800000	680000	560000	440000	320000	200000	80000

Table A.11: Active stock for the intensified ICT use scenario.

Product	2020	2025	2030	2035	2040	2045	2050
Smartphone	11249493	11275869	11276058	11276058	11276058	11276058	11276058
Tablet	2921383	3287608	3459773	3543004	3584069	3604656	3615113
Laptop	3617667	3675611	3676087	3676087	3676087	3676087	3676087
Desktop	774473	775369	775441	775445	775445	775445	775445
PC monitor	3161422	3162516	3162567	3162567	3162567	3162567	3162567
CPE	3853001	3854335	3854397	3854397	3854397	3854397	3854397
XR-headset	161666	762431	1665564	2578199	3490862	4403526	5316189
Security camera	620019	993149	1748672	2540511	3332367	4124223	4916079
Smart speaker	2177321	2501473	2981435	3466411	3951403	4436395	4921387
Wearable	2209981	3208595	4703000	6213095	7723239	9233382	10743525
Television	6809679	6819986	6820807	6820845	6820846	6820846	6820846

Table A.12: Active stock for the multi-functional ICT scenario.

Product	2020	2025	2030	2035	2040	2045	2050
Smartphone	11249493	10163193	8489641	6798286	5106877	3415469	1724060
Tablet	2921383	3078155	2857995	2469173	2001312	1495344	970622
Laptop	3617667	3451979	2945696	2394334	1842921	1291508	740094
Desktop	774473	724310	621582	506449	390173	273856	157539
PC monitor	3161422	2942081	2489535	2015160	1540775	1066390	592005
CPE	3853001	3854335	3854397	3854397	3854397	3854397	3854397
XR-headset	161666	1380585	3213574	5065850	6918185	8770520	10622855
Security camera	620019	625193	625230	625230	625230	625230	625230
Smart speaker	2177321	2182426	2182462	2182462	2182462	2182462	2182462
Wearable	2209981	2215162	2215199	2215199	2215199	2215199	2215199
Television	6809679	6464410	5629353	4620892	3597898	2574772	1551645

Table A.13: Calculated use time per capita for the intensified ICT use scenario. Only products which require active input are included.

Product	2020	2025	2030	2035	2040	2045	2050
Smartphone	3.50	3.51	3.51	3.51	3.51	3.51	3.51
Tablet	0.45	0.50	0.53	0.54	0.55	0.55	0.55
Laptop	0.70	0.71	0.71	0.71	0.71	0.71	0.71
Desktop	0.15	0.15	0.15	0.15	0.15	0.15	0.15
XR-headset	0.02	0.54	1.18	1.82	2.47	3.11	3.75
Television	1.32	1.32	1.32	1.32	1.32	1.32	1.32

Table A.14: Calculated use time per capita for the multi-functional ICT scenario. Only products which require active input are included.

Product	2020	2025	2030	2035	2040	2045	2050
Smartphone	3.50	3.17	2.64	2.12	1.59	1.06	0.54
Tablet	0.45	0.47	0.44	0.38	0.31	0.23	0.15
Laptop	0.70	0.67	0.57	0.46	0.36	0.25	0.14
Desktop	0.15	0.14	0.12	0.10	0.08	0.05	0.03
XR-headset	0.02	0.45	1.28	2.19	3.12	4.05	4.98
Television	1.32	1.25	1.09	0.89	0.70	0.50	0.30

B

Appendix

Modelling of the data centre energy use

In this section the calculations for the data centre energy use are described in more detail. As mentioned in section 4.3.3, the data centre energy use is assumed to be constant in the multi-functional ICT scenario. For the intensified ICT use scenario the energy use is modelled to change due to increases in use time as well as adoption of AI. More specifically, the data centre energy use in year y, E_y, is calculated as follows

$$E_y = E_{y=2020} \cdot \frac{u_y}{u_{y=2020}} \cdot a_y, \tag{B.1}$$

where $E_{y=2020}$ is the baseline year estimate for the data centre energy use, u_y is the modelled use time per day and capita, and a_y is a factor which accounts for the effects of AI implementation. The assumptions made for the modelling of the use time can be found in Appendix A. The value of a_y is based on the example presented in section 4.3.3, where it is assumed that the AI implementation changes the energy use in line with a transition from normal Google searches to AI powered searches. The factor a_y is assumed to increase linearly from unity in 2020 to 23 in 2050, which is the ratio between the energy use from an AI powered search and a normal Google search $\left(\frac{6.9\,\mathrm{W\,h}}{0.3\,\mathrm{W\,h}} = 23\right)$.

For the intensified efficient ICT use scenario the calculation is further complemented with efficiency gains. To account for decreases in energy consumption both in the IT equipment as well as the surrounding infrastructure, the energy consumption is calculated as the sum of the IT equipment energy consumption, $E_y^{(\mathrm{IT})}$, and the remaining energy use, $E_y^{(\mathrm{other})}$, according to

$$E_y = E_y^{(\mathrm{IT})} + E_y^{(\mathrm{other})}. \tag{B.2}$$

The IT energy consumption is assumed to depend on the modelled changes in use time, AI implementation, and improvements in computing efficiency. The computing efficiency is modelled based on a relation suggested by Prieto et al. (2024) which is presented in equation 4.3. Combining these effects yields the following formula for the IT equipment energy use

$$E_y^{(\mathrm{IT})} = E_{y=2020}^{(\mathrm{IT})} \cdot \frac{u_y}{u_{y=2020}} \cdot a_y \cdot \frac{3 \cdot 10^{-273} \cdot e^{0.3122 \cdot 2020}\ \mathrm{GFLOPS/W}}{3 \cdot 10^{-273} \cdot e^{0.3122 y}\ \mathrm{GFLOPS/W}}, \tag{B.3}$$

where the IT energy use in 2020 was estimated using the power usage effectiveness in 2020: $E^{(\mathrm{IT})}_{y=2020} = \frac{E_{y=2020}}{\mathrm{PUE}_{y=2020}} = \frac{E_{y=2020}}{1.55}$. Furthermore, based on the definition of the power usage effectiveness presented in section 4.3.3, the remaining energy use was calculated as

$$E_y^{(\mathrm{other})} = E_y^{(\mathrm{IT})} \cdot (\mathrm{PUE}_y - 1)\,, \tag{B.4}$$

where PUE_y denotes the power usage effectiveness of the data centres. As mentioned in section 4.3.3, the PUE was modelled to decrease linearly from 1.55 in 2020 to 1.02 in 2050. In Table B.1 a summary of the values used for the calculations above is presented.

Table B.1: Summary of the values used for the calculations of the data centre energy use in the intensified ICT use and intensified efficient ICT use scenarios.

Value	2020	2025	2030	2035	2040	2045	2050
u_y [h per capita and day]	6.14	6.73	7.40	8.06	8.71	9.35	10.00
a_y	1.00	4.67	8.33	12.00	15.67	19.33	23.00
PUE_y	1.55	1.46	1.37	1.29	1.20	1.11	1.02

C

Appendix

Background system model

Table C.1: Activity names and location used in ecoinvent per product. The PC monitor emission values were converted to per unit emissions by multiplication with an assumed weight of 6 kg, based on Kalmykova et al. (2015).

Product	**Activity name**	**Location**
Global electricity, medium voltage	Market group for electricity, medium voltage	GLO
Sweden electricity, low voltage	Market for electricity, low voltage	SE
Smartphone	Market for consumer electronics, mobile device, smartphone	GLO
Tablet	Market for consumer electronics, mobile device, tablet	GLO
Laptop	Market for computer, laptop	GLO
Desktop	Market for computer, desktop, without screen	GLO
PC monitor	Market for liquid crystal display, unmounted	GLO
Television	Market for television	GLO

Table C.2: Assumed emissions from the production and transportation of one unit. The table only includes the devices which were not found in ecoinvent.

Product	Emissions [kg CO_2eq]	Source
XR headset	230	(Apple, 2024)
Security camera	68	(Hillerström & Troborg, 2010)
Smart speaker	60	(Apple, 2023b)
Wearable	25	(Apple, 2023a)

D

Appendix

Results

Table D.1: Emissions in kg CO_2eq per capita for the intensified ICT use pathway with background system SSP2-NDC.

Category (life cycle phase)	2020	2025	2030	2035	2040	2045	2050
User devices (production and transportation)	82	64	49	44	38	33	32
User devices (use)	6.2	6.0	5.8	5.6	5.1	5.1	3.4
Data centres (use)	20	50	64	66	52	36	32
Networks (use)	26	22	23	22	17	12	11
Total	133	142	141	137	112	86	77

Table D.2: Emissions in kg CO_2eq per capita for the intensified efficient ICT use pathway with background system SSP2-NDC.

Category (life cycle phase)	2020	2025	2030	2035	2040	2045	2050
User devices (production and transportation)	82	64	49	44	38	33	32
User devices (use)	6.2	5.2	4.4	3.7	3.0	2.6	1.5
Data centres (use)	20	10	3	0.5	0.08	0.01	0.002
Networks (use)	26	11	6	3	1	0.3	10^{-8}
Total	134	90	61	51	42	36	33

Table D.3: Emissions in kg CO_2eq per capita for the multi-functional ICT pathway with background system SSP2-NDC.

Category (life cycle phase)	2020	2025	2030	2035	2040	2045	2050
User devices (production and transportation)	82	58	41	34	27	21	19
User devices (use)	6.2	5.6	5.0	4.4	3.8	3.5	2.1
Data centres (use)	20	9.8	6.4	4.2	2.3	1.2	0.8
Networks (use)	26	13	8.5	5.6	3.1	1.6	1.1
Total	133	86	61	48	36	28	23

Table D.4: Emissions in ton CO_2eq per capita for the sensitivity analysis with adjusted baseline network energy.

Scenario	2020	2025	2030	2035	2040	2045	2050
Intensified ICT use	0.15	0.17	0.17	0.17	0.14	0.10	0.09
Intensified efficient ICT use	0.15	0.10	0.06	0.05	0.04	0.04	0.03
Multi-functional ICT	0.15	0.09	0.07	0.5	0.04	0.03	0.02

Table D.5: Total energy consumption (excluding user device production) in GW h for the sensitivity analysis with adjusted baseline network energy.

Scenario	2020	2025	2030	2035	2040	2045	2050
Intensified ICT use	2340	4370	6900	9870	13260	17080	21340
Intensified efficient ICT use	2300	2160	1760	1500	1300	1130	960
Multi-functional ICT	2340	2340	2340	2330	2320	2310	2300

Table D.6: Emissions in kg CO_2eq for the SSP5-Base pathway. The electricity values correspond to 1 kW h and the consumer electronics to emissions for the production and transportation of one unit. The Swedish electricity is kept constant at the baseline value, as the model gave unreasonably large numbers.

Product	2020	2030	2040	2050
Global electricity, medium voltage	0.708	0.454	0.463	0.435
Sweden electricity, low voltage	0.044	0.044	0.044	0.044
Smartphone	39	27	27	26
Tablet	88	61	62	60
Laptop	170	120	130	120
Desktop	220	170	170	170
PC monitor	380	300	470	290
XR-headset	230	200	200	190
Security camera	68	47	48	46
Smart speaker	60	52	53	50
Wearable	25	21	22	21
Television	380	290	290	290

Table D.7: Emissions in kg CO_2eq for products for the SSP2-PkBudg1150 pathway. The electricity values correspond to 1 kW h and the consumer electronics to emissions for the production and transportation of one unit.

Product	2020	2030	2040	2050
Global electricity, medium voltage	0.708	0.214	0.049	0.020
Sweden electricity, low voltage	0.044	0.044	0.037	0.015
Smartphone	39	16	8	7
Tablet	88	36	19	16
Laptop	170	80	40	40
Desktop	220	100	60	50
PC monitor	380	270	130	120
XR-headset	230	120	60	50
Security camera	68	27	14	12
Smart speaker	60	31	16	13
Wearable	25	13	7	5
Television	380	180	110	90

Table D.8: Per capita emissions in ton CO_2eq using the status-quo background system.

Scenario	2020	2030	2040	2050
Intensified ICT use	0.13	0.37	0.70	1.2
Intensified efficient ICT use	0.13	0.13	0.13	0.13
Multi-functional ICT	0.13	0.13	0.13	0.13

Table D.9: Per capita emissions in ton CO_2eq using the SSP5-Base background system.

Scenario	2020	2030	2040	2050
Intensified ICT use	0.13	0.25	0.49	0.71
Intensified efficient ICT use	0.13	0.10	0.11	0.11
Multi-functional ICT	0.13	0.10	0.11	0.10

Table D.10: Per capita emissions in ton CO_2eq using the SSP2-PkBudg1150 background system.

Scenario	2020	2030	2040	2050
Intensified ICT use	0.13	0.14	0.08	0.06
Intensified efficient ICT use	0.13	0.06	0.04	0.03
Multi-functional ICT	0.13	0.06	0.03	0.02

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