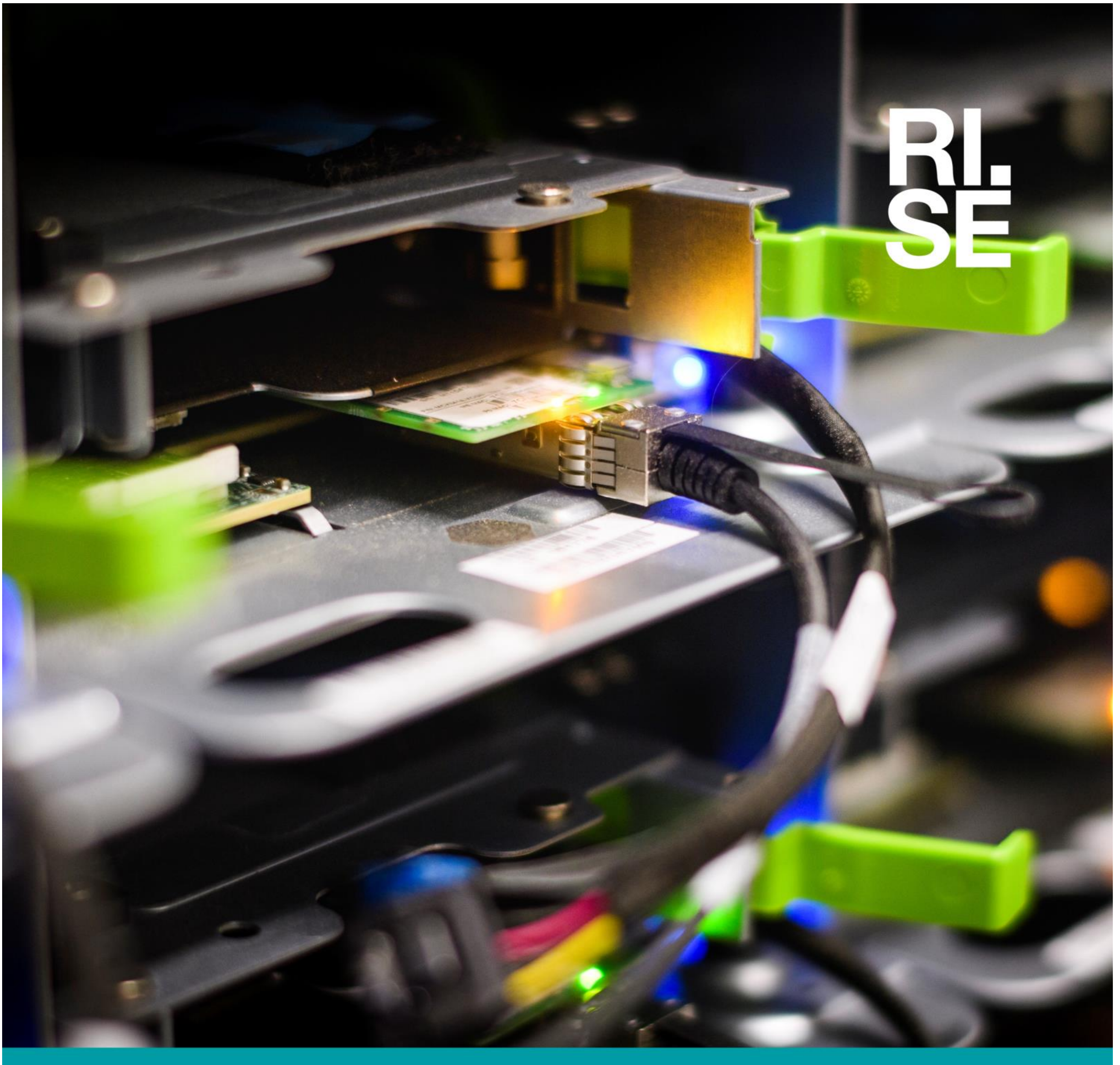

Energy Use in Data Centers and Digital Systems

Report to Swedish Energy Agency from RISE in the assignment "Consultancy service about energy use in data centers and digital systems".

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Summary

This report contains a basis to follow the development of energy use continuously for digital infrastructure and digital systems, in particular data centers, as well as its impact on the energy system.

The use of electricity in data centers has recently received attention by the general public, media and policy/law makers. Data centers are fundamental infrastructures for the society like roads. Data centers are central in the digitalization and for the ongoing green transformation of the industry. The energy use in data centers is around 1–2% of the global electricity use and far below the dramatic numbers shown in media.

The report covers data center infrastructures. A data center is the facility that hosts the computers we use when we access the web, use applications or when industries process data in the background. Most of the energy in an efficient data center goes to the IT servers. Data centers can be classified into categories and are of different sizes. Data centers in office buildings for the company internal use is usually smaller less than 300 kW and the cloud company facilities are large at above 10 MW. Crypto mining facilities are not included in this report.

To assess the energy use, a few methods are available. In the short-time frame of this study, RISE relies on already available reports, interviews and some statistics received. In the long run a governmental policy-based requirement on reporting from the data center operators will ensure transparency and quality of the assessment.

The development of the data center market in Sweden still follows what is outlined in a recent Swedish report by Radar (Wallin, Werner, & Olofsson, 2020). The last years Sweden has seen an increased activity by large cloud companies in Sweden. It has resulted in a higher growth rate of the energy use compared to European or global numbers. RISE assesses that the current energy use by data centers in Sweden to be 2,8–3,2 TWh during the year 2022 using calculations based on the Radar report.

Looking into the future is more difficult. Since more larger data centers still are under construction and will be built in Sweden and workloads from Europe will continue moving to Sweden and so it is reasonable that the trend for the growth of energy use will stay above EU average until year 2025. Due to the new tax regulations and current economic downturn, it will though be at a slower pace than between 2018–2022. RISE estimates half the growth rate of the Radar report due to this. RISE assesses and calculates the estimated energy use by data centers in Sweden will be 4,0–4,4 TWh per year by 2025. Beyond 2025 there are many uncertainties. A cautious estimate is 4,4–5,2 TWh per year for year 2030.

Data centers can play an important role in the integration with the energy systems. For example, can data centers perform peak-shaving and energy arbitrage as well as act on the frequency ancillary markets. Also, the excess heat from data centers can be used in industrial symbiosis with heating applications such as district heating networks or greenhouses. Another important aspect is that it is more to environmental impact of data centers than energy efficiency. Analysis of the life cycle of all equipment and the operations needs to be done as well as monitoring other metrics than energy use for example water usage.

Many new technologies are and will be developed to improve the energy efficiency and operations of data centers. Higher density of compute per square meter will require new cooling methods like liquid cooling, edge computing will require small compute nodes inside the networks and on-site production of electricity with fuel cells is another new development. Swedish industry is a leader in sustainable data centers. Many new innovations and products are coming from a growing industry sector. Recently a Swedish data center industry association has been formed.

The European commission is active to develop visions and strategies for the future of Europe. A policy program “Path to the digital decade” will ensure an increased use of digital services and hence data centers supported by the Green deal initiative. There are three new initiatives on energy efficiency, the Energy Efficiency Directive (EED) updated with data centers, the Corporate Sustainability Reporting Directive (CSRD) and The EU Taxonomy for environmentally sustainable economic activities, that are also impacting the data center industry with increased transparency of metrics from the data centers. A supportive activity is the EU Code of conduct that can help data center operators to assess and improve their operations. Also, other initiatives are ongoing like the Climate neutral data center pact, the IMasons Climate Accord and the Sustainable Digital Infrastructure Alliance.

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Glossary

ASIC	Application Specific Integrated Circuit
CAGR	Compound Annual Growth Rate
CDN	Content Deliver Network
CMOS	Complementary Metal Oxide Semiconductor
CO_2e	Carbon dioxide equivalent
CPU	Central Processing unit
GHG	Green House Gas
GPU	Graphical Processing Unit
HPC	High-performance computing
ICT	Information- and Communication Technology
IEA	International Energy Agency
LCA	Life Cycle Assessment
ML	Machine Learning
PUE	Power Usage Effectiveness, total energy divided by IT energy
SLA	Service Level Agreement
UPS	Uninterruptible Power Supply
XPU	X= Accelerated, One example is TPU Tensorflow Processing Unit

Introduction

Swedish energy agency has selected and asked RISE under the frame agreement, "Ramavtal angående Konsultstöd gällande Energikonsulter för Energimyndigheten Dnr 2022-9156, to create a basis to follow the development of energy use continuously for digital infrastructure and digital systems, in particular data centers, as well as its impact on the energy system.

The supportive information from this report will be used in the internal competence development and knowledge creation as well as being a basis for a report to the Swedish government from the Swedish Energy Agency (Energimyndigheten, 2022). The objective for the energy agency is to receive a proposal on a method to monitor and an evaluation of the current status of the energy use in data centers. The objective is also to increase the knowledge about technologies and European initiatives that will influence the development of the energy use in the sector for the future. There is also an interest in how data centers can interact with the energy system.

Electricity use in data centers is not understood

In recent times, the use of electricity in data centers has received some attention. The connection between energy use in data centers and the everyday life as a citizen is not clear for the general public. It is not well understood that the data centers, per se, do not use most of the energy, but all the digital services we use and must have in the modern world that is the cause of digital processing in data centers.

One report states that we visit a minimum of 40 data centers per day and "A day in our life" is described in the report (Fryer, 2022). It all starts already in the morning with our alarm clock in the phone creating a tick in the box at the phone service data center. All aspects of our life would not work without data centers such as to pay in the subway, stream a video, heat the housing, fill up gas in the car, participate in a video call, edit a document, send a tweet or any activity that is using digital services. One hour stop of all data centers would create chaos and end up in the highest warning for all critical sectors at MSB.

Another subject related to data centers that has received attention is the tax reductions for data centers with sizes larger than 100 kW. Riksrevisionen has done a review and written a report on the Government efforts to stimulate investment in data centers. It contains conclusions and recommendations to the government (Riksrevisionen, 2022). The assessment in the review was that the government has not ensured that significant effects of the government efforts to stimulate investments in data centers have been taken into account so that the efforts are effective with regard to business policy and energy policy goals.

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How data center really works and support society

A good illustration of how the internet works is shown in the Figure 1 from TechUK below.

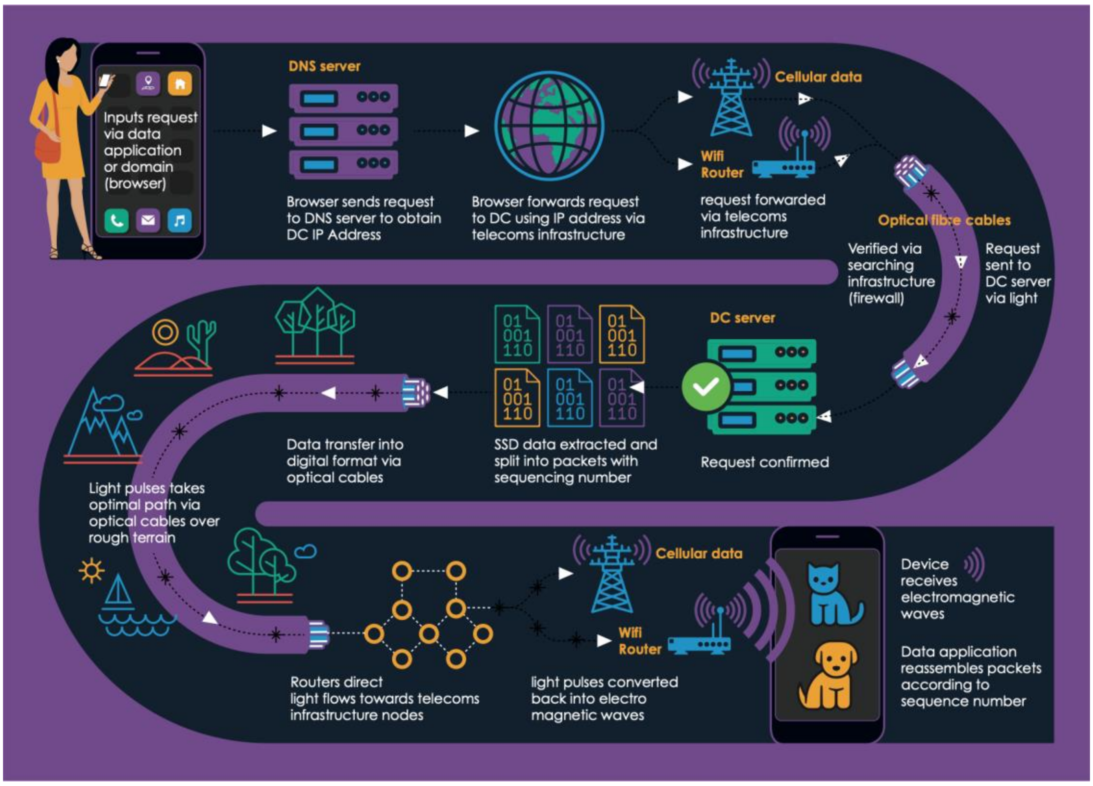

Figure 1: How the internet works (TechUK).

Our use of digital services, in the beginning of the infographics, triggers the use of the telecommunication mobile and core fiber networks and the information is sent over to the data center. The data center then processes the service in servers (computers) hosted in the facility. The result is then sent back over the communication networks to the user's device. All parts in the chain from device to the data center use a small amount of energy to create value for the user. Without all this infrastructure the apps in our phone, the web browsing, the TV streaming, the industry automation, the office work nor the green transformation would not work.

The other side of the energy use in data centers is that the use of information and communication technologies (ICT) will drastically reduce energy use in other sectors. The report Smarter2030 (Global e-sustainability Initiative, 2015) shows roughly 9.7 times savings if digitalization is used in other industry sectors. We all have experienced it during the pandemic when air travelling was exchanged to video conferencing. The reduction in environmental impact from the pandemic in the aviation industry was noticeable see Figure 2 below comparing the aviation industry and the ICT sector.

Fact checking of reported energy use

The energy use in the data center sector has also been compared to the aviation industry. It has been fact checked and it shows that the total ICT sector is at 0,7 billion tonnes CO_2e that is 1,3% of the global carbon impact and half of the aviation industry at 1,5–2,2 billion tonnes CO_2e. Data centers are less than 20% of the total ICT sector. It means that the data center industry is about 10% of the aviation industry. Important to note here is also that aviation supports only 1% of all humans whereas data centers are for nearly all people on the globe for many hours a day (Malmodin, 2022).

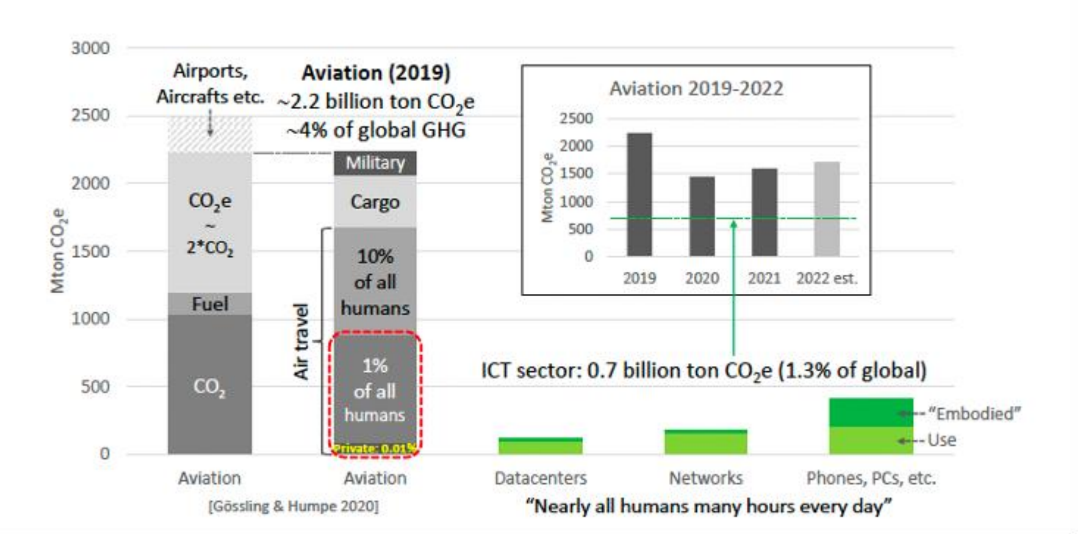

Figure 2: Comparing aviation with ICT (Malmodin, 2022).

Of course, the value of a few digital services can be and has been questioned for example the value of storing cat images, playing games, pornographic material and crypto currency mining based on proof of work methods.

Looking at the current energy use, as will be described later, the growth of energy use in data centers globally has not been near the growth of internet traffic, up 440% between 2015 and 2021, or data center workloads, up 260% between 2015 and 2021 (IEA, 2022) The data center energy use is up only 10–60% (or CAGR 1,5–8%) in 6 years thanks to innovation and developments in resource sharing (cloud), resource efficiency (software and facility) and server hardware efficiency (Moore's law). Also, data centers and transmission networks are responsible for only 1% of the energy-related GHG emissions according to IEA and 1–2% each of the global electricity energy use (IEA, 2022) (Hintemann, 2020).

Sustainability and data centers

There is also more to sustainability of data centers than energy use. The environmental impact of data centers is high if the electricity used is produced by fossil fuel. Sweden together with Norway can offer the lowest impact electricity that could help the rest of Europe operating data centers i.e. creating value inland instead of exporting electricity as raw material. Other impacts come from materials used in data centers for example copper, gold and silver in servers and steel and concrete in the building as well as from transporting goods and people.

The Swedish Environmental Protection Agency has had researchers at KTH to study the issue in more detail. In the report Digitization and the environmental goals (Francart & Höjer, 2019), the conclusion is that information and communication technology can have a very positive effect on the environmental goals or a negative effect. It therefore depends on the viewpoint.

Scope of the study

The report will cover data center infrastructures. Data centers are one out of three main parts of the digital infrastructure. Another name is the ICT infrastructure (Information and Communication Technology). The other two main parts are the Internet core network and the mobile network. The total ICT industry also includes the large part of devices such as mobile phones, laptops, IoT etc. connected to the networks as well as all the software that runs in both devices and infrastructure.

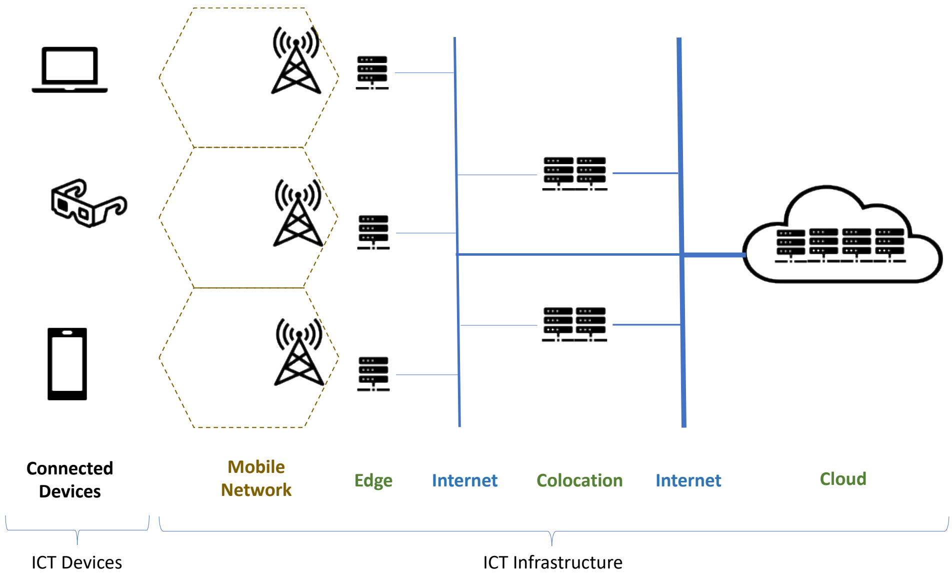

Figure 3: The ICT Infrastructure (only mobile network).

The above Figure 3 describes the different parts of the ICT infrastructure. The figure only shows the mobile network as the last mile connecting the devices. It can be inter-changed with the fiber network to homes and offices. The infrastructure in brown is the connectivity network, the blue part is the Internet core networks and the green part is the data center infrastructure. All parts of the infrastructure are connected to the Internet core network operating at different speeds and capacity exemplified with thinner or fatter connecting lines. The data center infrastructure is exemplified in this figure with edge nodes, colocation data centers and cloud data centers.

Crypto currency mining facilities that are one type of specific data centers are not in scope of this report but will be referenced when needed. All estimates of energy use exclude crypto currency mining except when specifically mentioned. Crypto currency mining energy use is addressed in a separate report (RISE, 2022).

Data center fundamentals

A data center is a mission-critical facility containing IT servers (computers) in cabinets (racks) and equipment supporting the IT operations, see Figure 4 below. The facility can be a separate building, an integrated as part (rooms) of another building or indoor/outdoor containers or cabinets. The part of the facility keeping the servers is called the white space and the part with supporting equipment is called grey space. The servers in the racks are for computing, storage and communication. The usual power density is below 10 kW per rack. The supporting equipment is for power distribution and power backup, cooling of servers with air and liquids, sensors and meters for monitoring of the operations, fire protection and mechanical ducting for air and pipework for liquids.

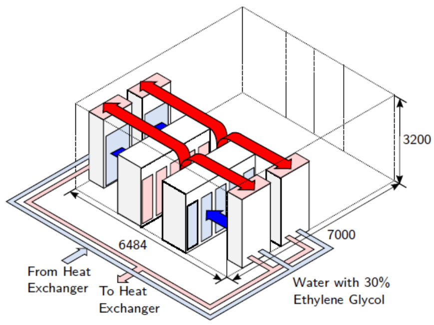

Figure 4: Data center white space with servers and air flows.

In an efficient data center most of the energy is used in the servers (70–80%) and the rest of the energy is lost in the supporting operation. All energy will become excess heat that can be used by the facility or in other heating applications such as district heating or industrial symbiosis with for example green houses.

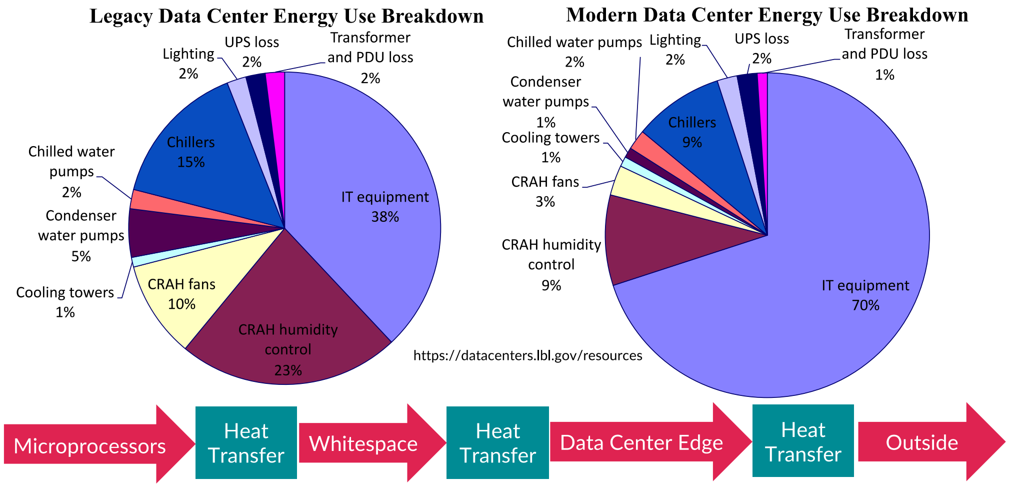

Figure 5: Data center energy use breakdown (Center of Expertise for energy efficient in data centers, 2022)

Above Figure 5 compares an old-style legacy data center or server room with a modern efficient data center. Below the pie charts is a heat flow chain described. The electricity distributed to the microprocessors and other electronics on the servers becomes heat when the processing is done. The heat is then transferred from the microprocessors to the whitespace (room) by air or liquid. From the room the heat is transferred to the wall or roof of the facility and then it is transferred to the outside air or water.

In a legacy data center most of the energy is used in the facility equipment fans, compressors, pumps and humidification. It can be as much as or more than 50–60%. A common KPI used in the industry that measure the effectiveness of the facility is the PUE measure (ISO/IEC, 2016). PUE stands for Power Usage Effectiveness and is not an efficiency metrics. It will only measure how effective the facility equipment part is and not how efficiently the IT is utilized. In short it measures total energy used divided by the IT energy used over one year. For a legacy data center, the PUE will be 1.8–2.5 or more. For a modern data center most energy will go to the IT equipment. A PUE for a highly effective facility is 1.1–1.3.

Data center categories and characteristics

The below Figure 6 from the EU taxonomy shows different parts of the data center infrastructure. This report will not cover on-device or end-user equipment like smart phones, cameras, laptops which is seen to the left in the figure. It will neither cover the backbone Internet network connecting all data center infrastructures behind the scenes nor the mobile network connecting wireless devices to data centers. The data center is the smallest part with respect to energy use and CO_2e impact compared to devices and networks (Malmodin, 2022).

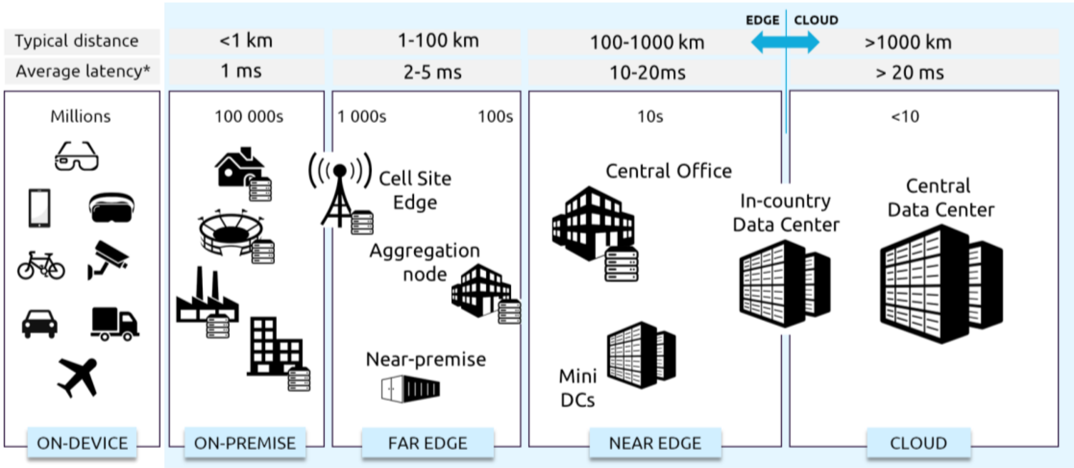

Figure 6: Data center infrastructure Cloud-edge (European Cloud Edge Investment, 2021).

The Figure 6 introduces also the two terms edge and cloud. Cloud data centers are the central data centers of large size far away from the end-user that host many of the public digital services like Facebook, Office 365, Twitter, Spotify and so on or private company/agency digital services like SAP, Sharepoint, CRM etc. Edge data centers are smaller scale data centers on-premise (internal organizations for data processing) or in public networks, such as far edge (in mobile networks for control and ML inference) and near edge (at or close to internet connect points for CDNs) also called metro edge since they are mostly in larger cities (The Linux Foundation, 2021).

The data centers are also possible to characterize by size (Wallin, Werner, & Olofsson, 2020). Small data centers are rated less than 300 kW and are mostly on-premise (own internal enterprises or governmental organizations) or far edge data centers (network edge). Medium sized data centers are rated 0,3–1 MW and are mostly near edge mini data centers (service providers/integrators), central office data centers (network operators) or in-country data centers (smaller co-location or metro edge with the CDN i.e. video streaming). Large sized data centers are rated between 1–10 MW and are larger in-country or smaller cloud data centers (co-location/cloud). Hyper sized data centers are rated above 10 MW and are large global in-country data centers (co-location) or large global hyper-scale data centers (cloud).

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Table 1: Size versus type of data center.

Radar categories	Own Internal		Service provider/Integrator			Commercial		Hyperscale	
EU taxonomy	On-premise		Far edge	Mini Data Center	Central Office	In-country	Large global in country	Large global hyperscale	
RISE examples / Radar sizes	Internal enterprise	Internal Government	Network operator	Service provider	Network operator	Colocation/ Metro edge		Cloud	Crypto currency mining
Small <300kW	Scania, LKAB	Customs and Tax agency	Telia, Stokab & Boliden						
Medium 0,3-1 MW		KTH-PDC, Social welfare		Atea, Banhof, CityNetwork	Telia, Tele2, Sunet	atNorth, Glesys, Acon, TietoEvry			
Large 1-10 MW	Ericsson					Stack, NData, Conapto			Enerhash, Bolooba, BBOperating
Hyper >10MW							EcoDC, Digital Realty	Facebook, AWS, Microsoft	Adaptic, HIVE, Barrage

The recent Radar report also classifies the data centers into Own internal, Service provider/ integrator (SP/SI), Commercial and Hyperscale data centers. The above **Table 1** combine the EU taxonomy and categories with the Radar definitions. There is not a one-to-one mapping between size and use case even if global and hyperscale data centers tend to be large-hyper size and own internal on-premise tend to be small to medium size.

RISE has added example categories and examples of data center operators for each category in **Table 1**. Examples of small data centers internal enterprises are Scania or LKAB, governmental agencies are the Tax agency or the Customs agency and network edge are nodes in the 5G network of Telia, in the Stokab network or in the mine of Boliden. Examples of medium sized data centers service providers are Atea, CityNetworks or Banhof, network operators are Telia or Tele2 and smaller co-location Atnorth, Glesys or Acon. Examples of large sized co-location data centers are Stack, Conapto or Hydro66. Ericsson is an outlier having two large internal data centers in Sweden. Examples of hyper-scale data centers are Facebook, Amazon, Microsoft, Equinix and Digital Realty.

RISE has also added a type category for crypto currency mining facilities. Examples of mining operators are Enerhash, Bolooba and BBOperating below 10 MW and Adaptic, HIVE and Barrage above 10 MW size. It is not in scope for this report and their energy use is not included in the estimates. A separate report covers crypto currency mining (RISE, 2022).

There are several different applications that run inside data centers with different characteristics. The use cases put requirements on how to execute the applications. Some use cases require low latency, other large storage capacity and others can be run distributed. Low-latency operation of applications such as control loops require that the data center is geographically located in the proximity of the use (milliseconds away), streaming services run typically distributed where the large storage of media is done in a centrally located data center (far away) and the local and often used media is located together with the streaming servers near-by the users in so-called metro data centers. HPC and long-term storage applications have no latency requirement and can be placed far away at energy efficient and sustainable locations.

Table 2 below shows different types of applications and their specific characteristics. Applications on the top of the table work fine for users connected to remote data centers (higher latency) and applications at the bottom require low latency connections from nearby data centers. Most applications can be implemented on top of virtualization platforms with the benefit of more efficient hardware utilization. Public and private clouds are based on energy efficient virtual machine or container software that will reduce the energy use.

Table 2: Applications and their characteristics.

Type	Response times	Data amount	Traffic amount	Cache	DC location
Cold storage	seconds	Gigabytes	Mb/s		remote
Off-line big data crunching	seconds	Gigabytes	Gb/s		remote
Chat/IoT type communication	100th milliseconds	kilobytes	kb/s		remote
Web/app rendering	100th milliseconds	Megabytes	Mb/s	Yes	remote
Streaming	10th milliseconds	Gigabytes	Mb/s	Yes	mix
Real-time conferencing	10th milliseconds	Megabytes	Mb/s	Yes	mix
Real-time analytics	milliseconds	Megabytes	Gb/s		proximity
Transaction based/control loops	milliseconds	kilobytes	kb/s		proximity

The data growth due to the digitalization is necessary and useful since it is the basis for a large GDP growth (Sundström, 2016). ICT helps to solve the challenges in urbanization, efficiency of society and industries, support development in poor regions and with an ageing population that all need solutions to make everyday life better.

Method for assessment of the energy use for data centers in Sweden

The Swedish Financial Supervisory Authority (Finansinspektionen) has made a methodology analysis report to assess the energy consumption for the extraction of crypto assets in Sweden (Malmén, 2022). Some of these methodologies can be used to map the energy consumption for regular data centers in Sweden. The report contains 9 different methodologies, of which 7 can be used for data centers in general, (not method 3 and 8).

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Table 3: Methods to assess the energy consumption for the extraction of crypto assets in Sweden (Malmén, 2022)

Nr	Name of method	Description
1	**Increased transparency requirements in the electricity distribution sector**	When the electricity companies sell electricity to data centers, additional transparency requirements could be introduced on the type of business that will be conducted in the data centers. A division into different categories, not only to analyse crypto mining. For example, reporting on electricity used for transmission, lighting, server operation, cooling and other. But also, which business, i.e., the purpose of the server environments in categories such as data storage, calculations, application servers, crypto mining.
2	**Increased transparency requirements for data centers**	When data centers deliver electricity to their customers in the center, they must be required to be able to report what type of business their customers conduct in the data centers.
3	**Cambridge University (CU) - Energy use and geographical distribution**	Using the analysis compiled by CU to calculate the total Swedish electricity consumption, and possibly regional breakdown. Cambridge calculates 1) total energy use for bitcoin, 2) in which country the electricity is used for mining and 3) which emissions the operation likely involves. By combining 1) and 2) it is possible to calculate the Swedish electricity consumption per month. In the geographic estimation (2), a higher resolution than country alone can be obtained in theory (region level). However, these data points are currently only shared between one mining pool and Cambridge, the remaining three mining pools only report on country resolution.
4	**Network analysis**	By analysing the Swedish internet traffic, mining actors can potentially be located. Provided they don't use VPN methods. By also analysing the traffic sent to mining pools, theoretically the extent of the hash rate could also be assessed. And thus, a theoretical estimation of the electricity use (though not significantly reliable)
5	**Survey to known data centers**	By asking data center operators which activities are conducted and how electricity use looks per sub-area, an estimation of the crypto-mining can take place
6	**Tax agency – VAT reporting**	The tax reduction for crypto mining equipment could be used to measure scale and follow trends
7	**Tax agency – tax return**	Miners request from SKV the return of VAT on electricity they paid (will probably be removed).
8	**Customs – import of equipment**	Import of ASIC-computers. Potentially, the Swedish Customs Service has information on what type of computer equipment is imported into Sweden.
9	**Visual analysis of data centers**	The equipment used for bitcoin mining can be visually identified. Through the model, it is also possible to calculate estimated electricity consumption.

RISE assesses that method 1 combined with method 2 constitute the most reliable and long-term method for measuring electricity use from data centers in Sweden. However, it will not be useful as a method for this report since the method requires some legislative changes and a long period of data collecting. Many of the suggested methods require long periods of data collection, such as method 4, 5, 6 and 9. Additionally, method 3 and 8 are focused on crypto currency mining. Method 7 may be fast, but it is not guaranteed to report all data centers or mining operations, since not all claim tax return. It can also be difficult to distinguish miners from other operations in the data centers. Method 7 will also not be an option for the future since the tax reduction will disappear.

To increase the reliability of the collected data, RISE has combined several methods and made an estimation of the energy use. For this study with a short time frame of three weeks the following combination of methods that was used:

- A literature study was used to identify stakeholders for the surveys, as well as trends, enablers, and advantages.
- Statistical data and quantitative data were collected based on a range of data sources.
- Semi-structured interviews were used to discuss a list of questions with stakeholders.

Figure 7: The methods used to assess the energy use for data centers in Sweden will be statistical data (green), literature study (Blue) and semi-structured interviews (yellow). All the inputs will then be analyzed to quantify the total energy consumption of data centers in Sweden (cloud).

The data center industry is developing fast, therefore flexibility is needed in the techniques to describe, analyze and forecast its developments. Hence, the methodology toolbox contains a wide variety of techniques, but also remains flexible to be able to switch to different approaches to solve issues.

To ensure reliable and accurate data sources RISE has collected data and information from several data sources. RISE has collected qualitative and quantitative information on the market developments from both Swedish and international companies. Despite this portfolio of methods, it can still be hard to map the energy usage in small scale data centers.

Foremost because, the small-scale data centers are in-house and might be unknown to the public as well as they might not have applied for tax reduction.

Collecting information from companies, especially commercially sensitive information, may be a challenge as companies will be reluctant to share, especially if it is uncertain for them who will have access to these data. To overcome this, RISE has ensured that all participants are aware of the purpose of the data collection and clearly communicate the process for handling any sensitive data or information. Sensitive data has been anonymized and presented only in aggregate form. Examples of questions to the interviewees were if the Radar report was reliable, how the development of energy use looks like and how the development in Sweden was, is and will be compared to Europe.

To make an assessment of the energy use for data centers in Sweden RISE used the selected combination of methods described above. The report "Datacenter i Sverige 2020–2025", by Radar Ecosystem Specialists (Wallin, Werner, & Olofsson, 2020) was used as a baseline. It is the latest and most reliable source for Sweden as stated by all interviewees. RISE then compared it with global reports and interviews, assessed the changes in energy use growth rates for the periods 2020–2022, 2023–2025 and up to year 2030 and then calculated the energy use using the growth rates. The interviews were done with the Swedish Data Center Industry Association, Business Sweden, Vattenfall, Nodepole, Financial Supervisory Authority and the Swedish Tax Agency.

Assessment of the current situation for data centers in Sweden

Sweden has good conditions for stimulating and attracting investments in data centers, from both Swedish and international actors. Examples of advantages are a cool climate, a well-developed broadband infrastructure, a reliable electricity supply with relatively low electricity prices and a stable political climate (Wallin, Werner, & Olofsson, 2020).

Development of the data center market in Sweden 2020–2022

To start with the Radar report from 2020, it shows the number of data centers compared with a report from Boston Consulting group (BCG) 2016 (Warrenstein, Lind, Sundström, & Deutscher, 2016) see Figure 8 below. The trend of decreasing number of smaller data centers (<0.3 MW), mostly on-premises server rooms, is supported by other reports (Kamiya, 2021) (Masanet, Shehabi, Lei, Smith, & Koomey, 2020). The number of Hyper sized data centers (>10 MW) are 8 according to the report and it is probably two Meta in Luleå, three AWS in and around Eskilstuna, one Equinix and one Digital Realty in Stockholm and one EcoDC in Falun.

RISE assesses that AWS and EcoDC were not fully utilized during 2020 based on information from Business Sweden and the Data Center Industry Association. Since then, the number of Hyper sized facilities has increased with three Microsoft data centers in Gävle/Sandviken to 11 in total. RISE assesses the situation now two years later that the number of smaller data centers has continued to decrease, for example have all communities in Norrbotten joined forces in one data center, as reported in global/European reports. Large sized (1–10 MW) has increased slightly since a few Medium sized (0.3–1 MW) have grown and are now counted as Large sized. Then AWS as well as EcoDC are more utilized now in 2022 while the new Microsoft data centers are not fully utilized yet according to Business Sweden and the Data Center Industry Association.

Antal datacenter Sverige	**Små** <0,3MW	**Medel** 0,3–1,0 MW	**Stora** 1–10 MW	**Hyper** >10 MW
Radar insamlad data 2020	2100	125	42	8
Av BCG angivna data	3000	110–120	20–30	5

Figure 8: The number of data centers (Wallin, Werner, & Olofsson, 2020).

Development of the data center energy use in Sweden 2020–2022

Next is the energy use and for this the Radar report estimates the current total energy use in 2020 to be 2,4 TWh per year with an average power of 276 MW, see Figure 9 below. Note that the wrong units are used in figure 9. It should be GWh instead of MWh in the title of the figure and MW in the table. Noticeable is that only five Hyper-scalers (3 AWS and 2 Meta) are counted in the Hyper size category. The other three in the Hyper size category seem to be counted in the Commercial type energy use category. RISE assesses that this total sum for energy use is the best estimate known since the analysis by Radar of total number of data centers and the shares of small, medium, large and hyperscale seems well balanced and reasonable.

The Radar report has not differentiated between different use cases. So included in the numbers are the energy use by crypto currency mining facilities. Based on the Cambridge bitcoin data for years 2019 and 2020 (Cambridge Centre for Alternative Finance, 2022) of 0,025 TWh and the Nodepole interview (Wikman, 2022) the size was found to be so small, estimated to about 0,04 TWh per year in total, that it did not impact the calculated projection for 2020 and forward. In this report crypto mining energy use is excluded due to the need to study it separately and it is covered in a separate report (RISE, 2022).

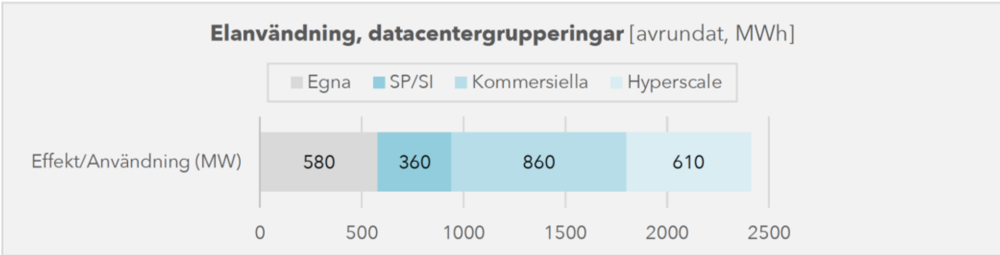

Figure 9: Energy use per data center type category in Sweden (Wallin, Werner, & Olofsson, 2020).

To help predict the future energy use the Radar report has estimated the growth rate in MW, see Figure 10 below. The average yearly growth rate is estimated to be 13%, with a reduction for Own type data centers, a small 2,7% growth per year for Service provider type data centers, a medium 8% growth per year for Commercial type data centers and a large 41% growth per year for Hyperscale type data centers.

		Inst. Effekt 2020	inst. Effekt 2025	Tillväxt	CAGR	
	Egna datacenter	275	274	-0,5%	0,0%	
Datacenter-industrin	Hyperscale DC	99	551	460%	41%	DC-industrin +148% (5 år) +19,9% årligen
	Kommersiella DC	181	262	45%	8%	
	SP/SI DC	88	101	14%	2,7%	
	Total	643	1188	**85%**	**13%**	

Figure 10: Installed power in MW and growth rate per data center type category (Wallin, Werner, & Olofsson, 2020).

The Radar report also describes the utilization per type category in Figure 11 below. The average utilization being 43% for all data centers. For the Own data center type category, the utilization is 24%, for hyperscale 71%, for commercial 59% (according to the picture in the report) and for Service provider type category 47%. Comparing the average power with installed power for the types of Commercial data center the correct utilization rate is 54%, that has been used in the calculations of this report.

	Inst. Effekt 2020	Medeleffekt	Utnyttjandegrad
Egen	275	66	24 %
Hyperscale	99	70	71 %
Kommersiella	181	98	59 %
SP/SI	88	41	47 %
	643	276	43 %

Figure 11: Power in MW and utilization per data center type category (Wallin, Werner, & Olofsson, 2020).

Comparing with global numbers, the International Energy Agency (IEA) reports a change from 200 TWh per year 2015 to 220–320 TWh per year 2021 for global data center energy use (IEA, 2022). That is a 10–60% growth rate or CAGR 1,5–8% despite a growth of data center workload of 260%. This is in-line with the more modest calculations and reports of historical growth numbers in reports comparing different energy use studies in Figure 12 and Figure 13 below (Montevecchi, Stickler, Hintemann, & Hinterholzer, 2020) (Mytton & Ashtine, 2022) (Kamiya, 2021).

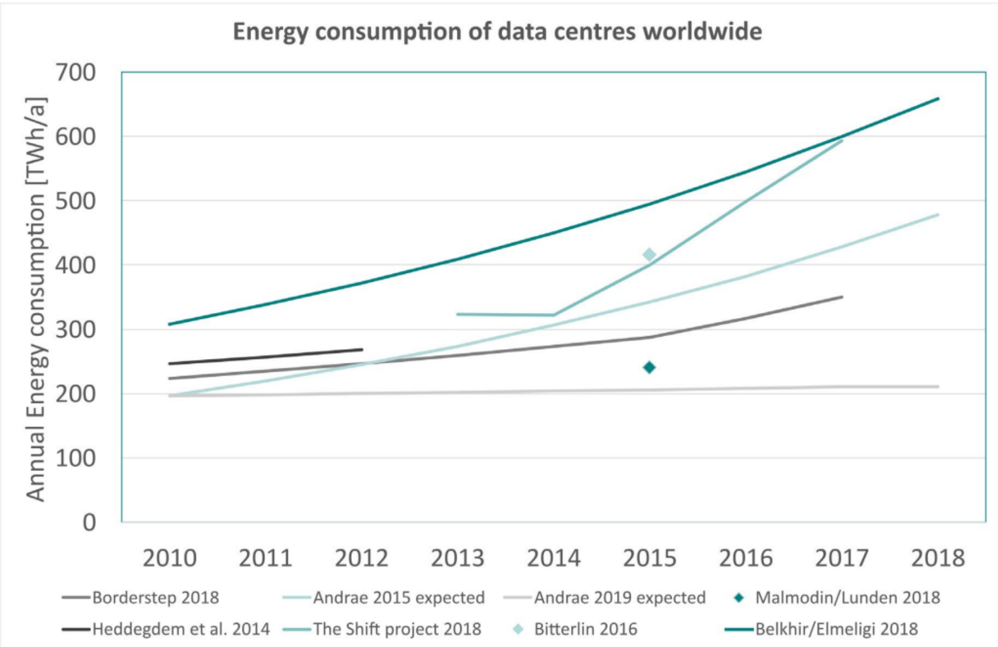

Figure 12: Different energy use calculations and estimates of use before 2018 (IEA, 2022).

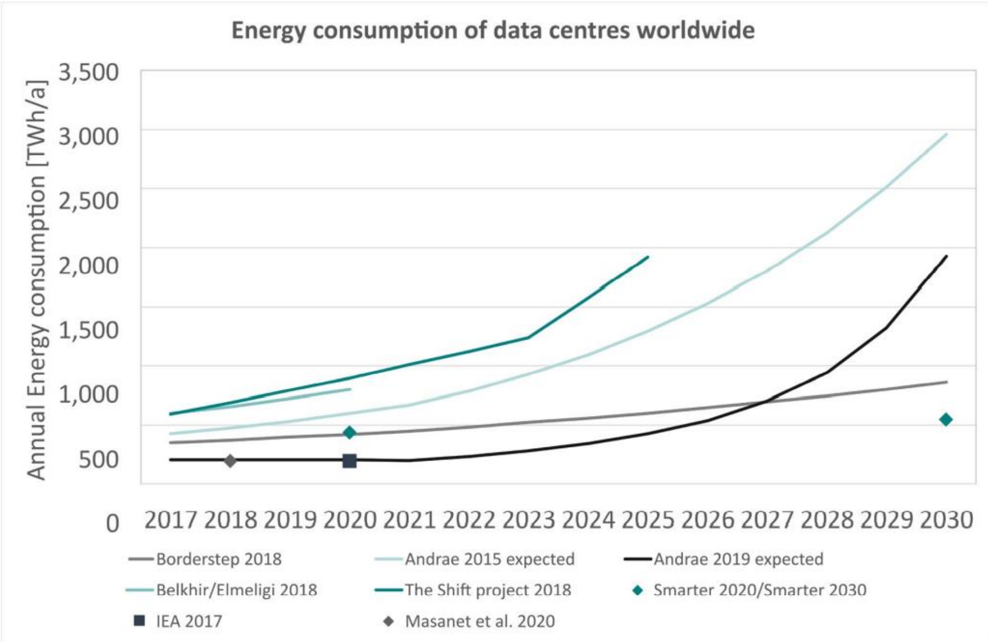

Figure 13. Different energy use calculations and estimates of use after 2018 (IEA, 2022).

To estimate the change in energy use from 2020 to 2022 in Sweden the IEA growth rates can be used as a baseline. The result is 2,48 TWh for 1,5% CAGR to 2,8 TWh for 8% CAGR. Taking the RADAR average growth rate 13% CAGR we get 3,1 TWh per year year 2022. Taking into account the difference in growth rates and utilization between categories according to the report we get 3,2 TWh per year for year 2022.

RISE assesses that the growth due to new hyper-scalers establishing in Sweden is still larger than an average global hyperscale growth based on the interviews and the knowledge about new facilities in Sweden. The growth rate of 41% for hyperscale data centers in Sweden as in the Radar report was assessed as reasonable. For example, was AWS coming in full operation and still four new Microsoft facilities have been built and start coming on-line. The move of cloud and HPC workloads from other parts of Europe mostly Germany to Sweden make the increase in energy use at an 8% CAGR (the high-end IEA estimate) for commercial data centers reasonable. All larger local cloud and co-location providers are growing with new international contracts according to the interviews.

The current situation of energy use in Sweden in 2022 is then between 2,8–3,2 TWh. The low-end estimate is based on the high IEA growth rate of 8%. The high-end estimate is based on the Radar model of 13% average growth rate is used to calculate the growth per type category and summarizing the energy use using the utilization rate.

Development of the Data center's energy use going forward

Data center energy use predictions far into the future are difficult to make. For that scenario modelling is needed and more time is required to develop the scenarios. The longer-term development depends on power availability in Sweden, policy frameworks for sovereignty, taxes and data center usage, data sharing lawmaking and uptake of new technologies that will increase demand on data center capacity for example IoT data use, Metaverse, AI applications, edge computing or 5G-6G. Other areas that impact the energy use are energy efficiency improvements of current ICT technologies based on resource sharing and Moore's law and development of new technologies such as neuromorphic or quantum computing.

Development and drivers of the global data center market beyond 2022

For a shorter period of time until 2025 and maybe up to 2030, a linear development could be expected. Efficiency improvements based on Moore's law and cloud resource sharing are expected to flatten beyond 2025. It will make the inherent improvements of energy efficiency of server and software technologies to diminish that could result in an increase of energy use. However, it can also cool down the increase in demand if improvements in processing capabilities are slowed down. Strong efficiency improvements such as lower PUE, more use of resource efficient cloud and improved compute and storage hardware, see Figure 15 below, have helped to limit growth in energy demand from data centers globally. The question is if this will continue beyond 2025.

Comparing internet traffic, data center workloads with energy use 2010–2020, as in Figure 14, it can be clearly seen that the data center energy use development is relatively flat compared to the increased traffic and workloads (Masanet, Shehabi, Lei, Smith, & Koomey, 2020) (IEA, 2021) (Cisco, 2018).

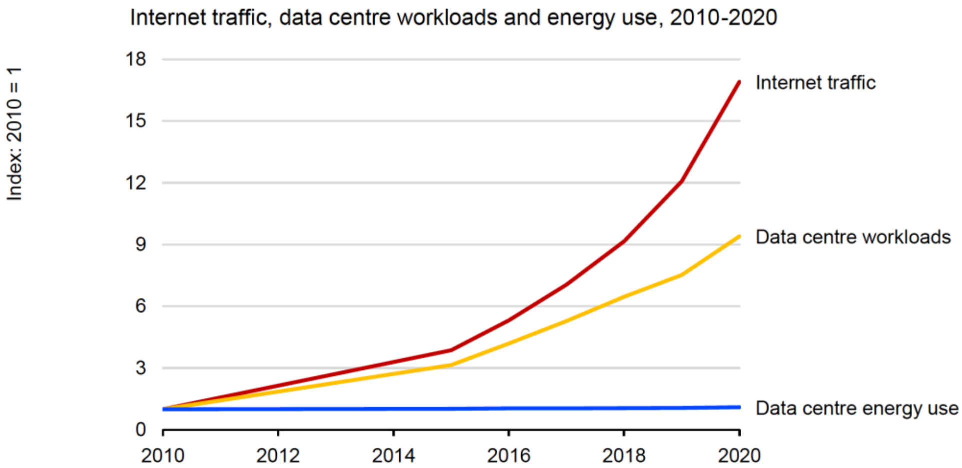

Figure 14: Global data center energy use trends (IEA, 2021).

Trends that drive the energy use in data centers are shown in Figure 15 below (Masanet, Shehabi, Lei, Smith, & Koomey, 2020). Growing demand on traffic, storage and workloads and growing installed base of compute and storage drive an increase in services. Facility, server and storage equipment and cloud computing resource sharing efficiency improvements drive a decrease in services.

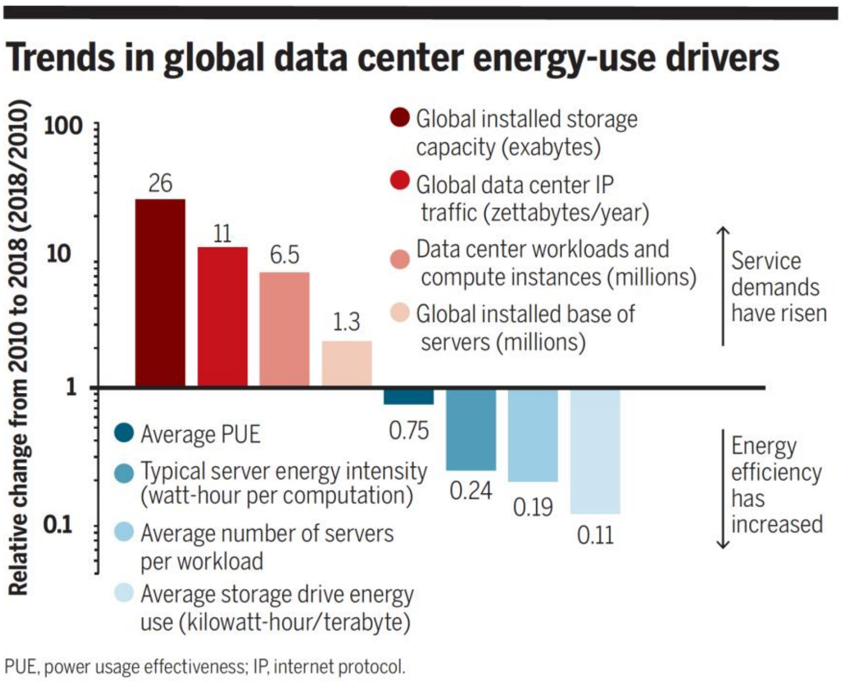

Figure 15: Trends in global data center energy-use drivers (Masanet, Shehabi, Lei, Smith, & Koomey, 2020).

A missing driver in Figure 15 is the increased interest by software developers and machine learning data scientists to improve the software using more efficient programming languages, compilers, software platforms, optimized code and to improve ML-model and dataset sizes as well as compute algorithms. Hardware acceleration is another efficiency improvement track that will decrease the service demand and hence decrease the data center energy use.

A well-referenced figure showing the USA data center energy use is in Figure 16 below. It was created in 2016 and was used to predict the growing demand and the energy use by data centers. Some optimistic scenarios were developed where the annual energy use could decrease. The Current Trends is shown as a black dashed curve, IM+HS in pink is when Improved Management (IM) in blue and Hyperscale Shift (HS) in red are added together. BP+HS in orange is when Best Practices (BP) in green and Hyperscale Shift (HS) in red are added together.

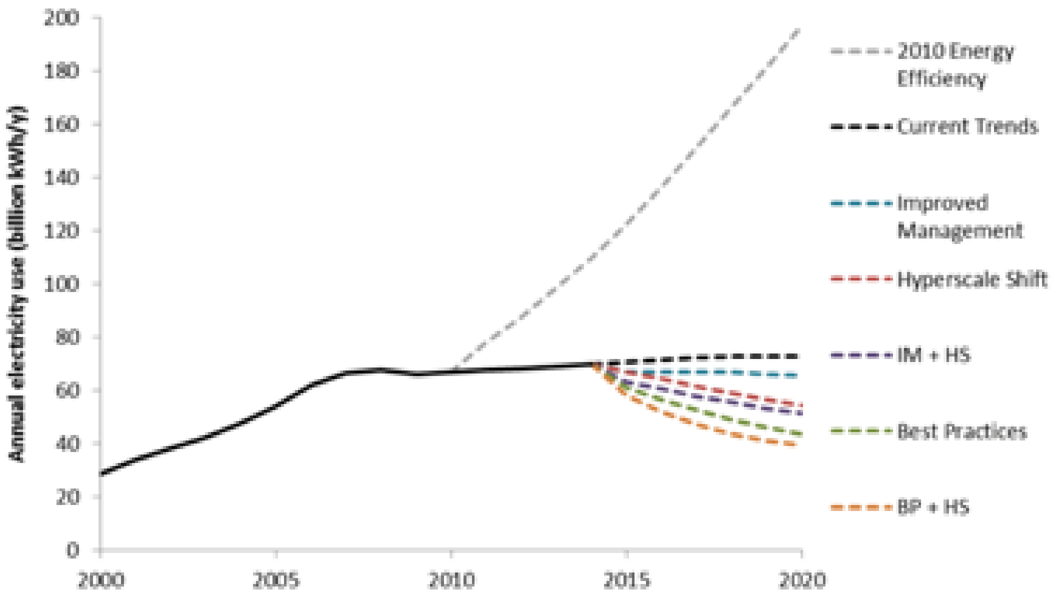

Figure 16: United states data center electricity use (Shehabi, 2016).

The development between 2015 and 2020 has though shown to be at the "Current Trends" curve with a slight increase globally (IEA, 2022). The demand has slightly outgrown the envisioned improvements. Also, regions with less developed local markets and few hyperscale deployments going into 2015 have shown greater increase in energy use like it has been shown in the Nordic market.

Data center energy use of video streaming

Looking at different areas of digital services the dominating service with respect to data traffic in the mobile and fixed network is video streaming, see Figure 17 below. It is a use case that drives storage of video and media processing during use sessions. Together with ads and machine learning heavy services like Facebook, Twitter, Instagram, search etc. video processing is a demand driving digital service.

Image storage on hard drives and tape drives are energy drivers when viewed only. Gaming could be classified as video streaming. Video conferencing/calls is a growing digital service that drives energy use due to heavy media processing. IoT data processing is not yet developed, and regular phone or text messaging are not highly demanding services. Industry automation and its use cases are not well developed either. Still use of big data and AI applications are the growing use cases.

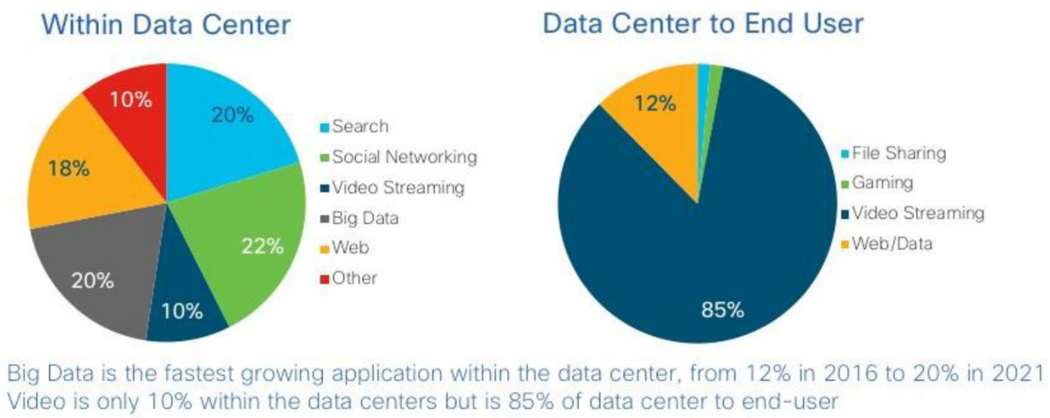

Figure 17: Data center traffic by application2021 (Cisco, 2018).

Since video streaming is dominating, several alarming studies have been published on video streaming using energy equivalent in size of an African country for one viral video clip. For one hour of Netflix streaming 2,5–6 kWh has been published by the media. All are wrong since they make the wrong assumption that increase in data means increase in energy and the wrong metric used is then kWh/GB (Malmodin, 2022).

A recent study by the Carbon Trust with partners shows another story shown in Figure 18 and Figure 19. The study concludes that one hour of video streaming is 180 Wh with the screen and home router being the dominating energy users. The environmental impact depends on the country of the user. The average in Europe is 56 gCO_2e/hour (DIMPACT and Carbon Trust, 2021).

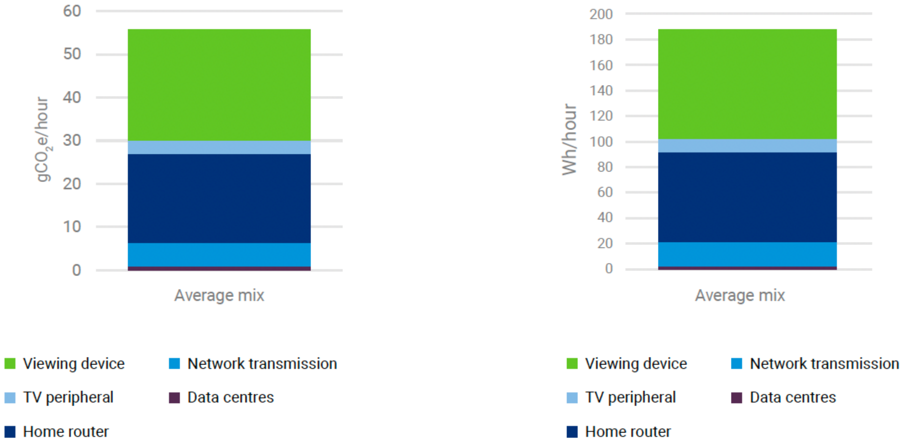

Figure 18: Estimated emissions and energy use from one hour of video streaming (European average in 2020) (DIMPACT and Carbon Trust, 2021).

Looking at Sweden the average environmental impact is 3 gCO_2e/hour compared to 76 gCO_2e/hour for Germany. The study has also looked at the contribution by each component. It concludes that data centers contribute with only 1% of the energy use.

Video streaming component stage	Emissions (gCO_2e/hour streaming)	Energy consumption (Wh/hour streaming)	% of total
Data Centres	<1	1	1%
Transmission Network	6	20	10%
Home Router	21	71	38%
TV Peripheral	3	10	5%
Screens	25	86	46%
Total	56	188	100%

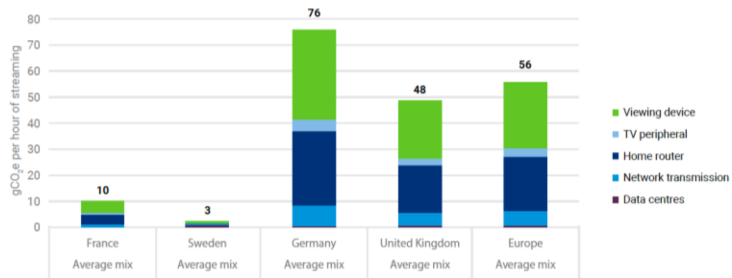

Figure 19: Estimated emissions from video streaming by region and component in 2020 (DIMPACT and Carbon Trust, 2021).

Assessment of the future for data centers in Sweden

Development of the data center market in Sweden beyond 2022

Depending on policy making, Sweden can take a leading role in Europe. Sweden has been regarded as being a stable political country in many studies on site selection for data centers. With the recently announced removal of the industry tax reduction the political stability scoring will be lower. To make large investments, companies aim to minimize risk and reduce uncertainties (Wallin, Werner, & Olofsson, 2020).

On the other hand, European policy making is going in the direction of requirements on energy efficiency and use of renewables for data center operations (European Commission, 2022). That will make Sweden an interesting place to move compute loads to. It has already started with a few German car manufacturers moving HPC workloads to Sweden. Sweden can contribute to a more sustainable Europe since the green industry and societal transformation needs to be supported by sustainable data center operations. Also, with experience of sustainable developments and innovation among research and product companies in Sweden the interest for that will increase, see the chapter on Innovations in the Swedish data center industry below.

With the drive for sovereignty, GDPR and keeping Swedish derived data in Swedish data centers a large amount of the Swedish workloads is handled in Sweden and will stay there considering sustainability aspects as well. Now when international cloud providers have established in Sweden even more digital services with Swedish data usage has moved back to Sweden. When Google, now being in Helsinki, has started its operation in Sweden as well in a few years, then most of the Swedish data, digital service and data center use will reside in Sweden except when companies need to be close to its customers for example Spotify or Ericsson.

Taking the future development and the data center use drivers into account some predictions have been made by (Montevecchi, Stickler, Hintemann, & Hinterholzer, 2020) in Figure 20 and (Malmodin, 2022) in Figure 21 below. One example is that Europe will go from about 70 TWh to 85 TWh in 10 years according to Borderstep (the trend projection in grey dashed line). That is a 2% average CAGR which is much lower than Radars estimate on 13% average CAGR in Sweden. A global estimate is done by Malmodin showing an increase from just about 200 TWh to 280 TWh in 10 years. That is 3,4% average CAGR.

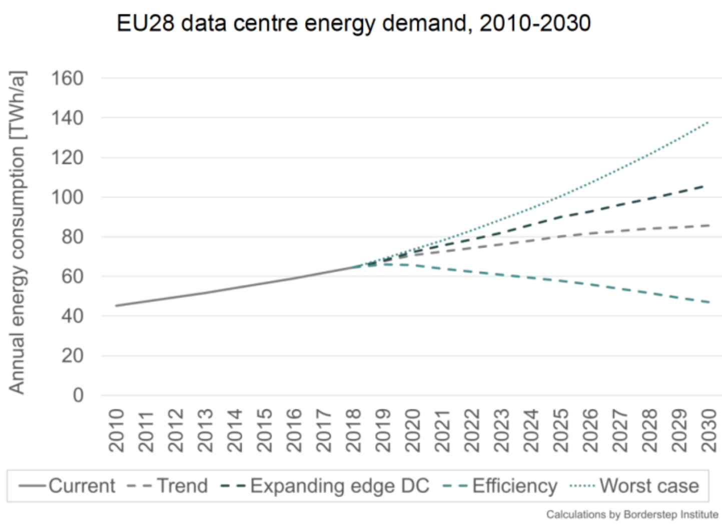

Figure 20: European data center energy projections (Montevecchi, Stickler, Hintemann, & Hinterholzer, 2020).

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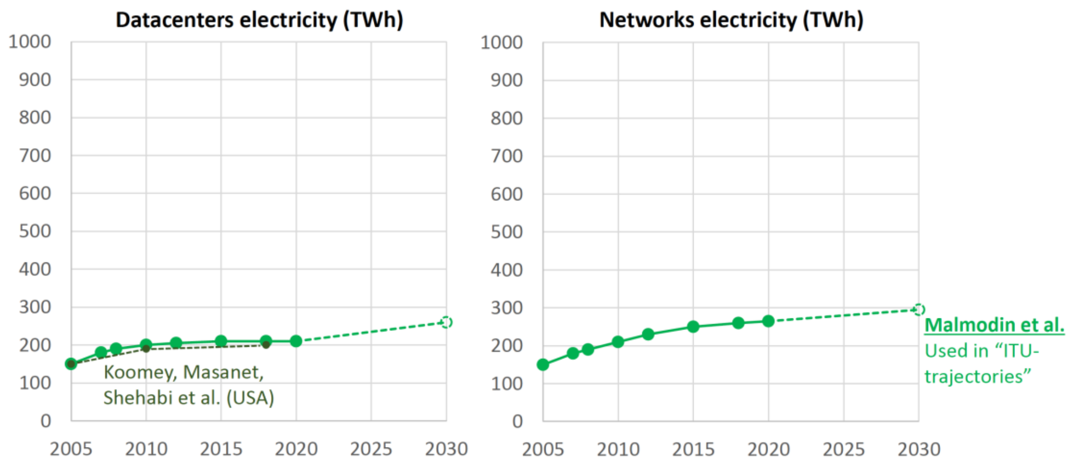

Figure 21: Data centers and networks over time (Malmodin, 2022).

Development of the data center energy use in Sweden beyond 2022

Taking the European average growth rate of 2% CAGR starting at 3,0 TWh (mid value of the Swedish assessment by RISE) in 2022 we get 3,2 TWh per year by 2025 and 3,5 TWh per year in 2030. With the global growth rate of 3,4% CAGR we get 3,3 TWh per year for 2025 and 3,9 TWh 2030. Using the Radar report growth rate and considering the difference in growth rates and utilization between categories according to the report we get 5,7 TWh per year in 2025 and 22 TWh per year by 2030. Comparing the Radar estimate for 2030 with the derived value using European average growth rate the conclusion is that the Radar growth rates are unrealistic outside the period 2018–2022 when many hyper-scalers were establishing in Sweden.

RISE assesses that the growth due to new hyper-scalers establishing in Sweden until year 2025 will still be larger than an average global hyperscale growth with four Microsoft facilities coming in full operations, one new Meta facility is being built and soon coming on-line and a planned Google facility is to be built. Due to the new tax regulations and current economic downturn, it will though be at a slower pace than between 2018–2022. The move of cloud and HPC workloads from other parts of Europe mostly Germany to Sweden will continue but also at a slower pace. RISE estimates, based on the interview input and the known new builds, it to be around half the growth rate in the Radar report, due to the current tax and economic situation as well as the growth happens from a higher level of energy use.

The increase in energy use for hyper scale will then be at 21% CAGR and for commercial data centers at 4% CAGR (half the high-end IEA estimate) until year 2025. The utilization rate per type category in the Radar model will still be reasonable until year 2025. Then The energy use in Sweden year 2025 will be between 4,0–4,4 TWh per year. It means an increase of 75% in 5 years from the Radar report year 2020 if no dramatic changes happen in technology, policy making or demand.

It is much more difficult to predict what will happen after 2025. A cautious prediction is that Sweden will look much more like the rest of Europe since many of the hyper-scalers already are established then. So, an average growth rate of 2,0–3,4% CAGR will take us to 4,4–5,2 TWh per year in 2030. It means a doubling of energy use in 10 years from year 2020.

A summary of the projections is shown in Table 4 below. The energy use in the columns is for Sweden only, using the growth rates from different sources. Comparing Radar growth rates to global predictions by IEA or European prediction shows that the growth rates are extreme and are only valid for the period 2018–2022 when all hyperscalers were establishing in Sweden and started operations. The growth rates will slow down now when the development is from higher levels and new establishments will have smaller relative sizes. The assessment by RISE is in the last row and uses as described above the Radar growth rate 13% for the period 2020–2022, the IEA global high growth rate 8% for the period 2022–2025 and the European average growth rate 2% for the period beyond 2025.

Table 4. Summary of calculated using different growth rates to calculate energy use in Sweden.

	Average growth rate	Energy use 2020	Energy use 2022	Energy use 2025	Energy use 2030
Radar SE	13	2,4	3,2	5,7	22,0
IEA Global high	8	2,4	2,8	3,5	5,2
IEA Global low	1,5	2,4	2,5	2,6	2,8
EU average	2		3,0	3,2	3,5
Malmodin Global	3,4		3,0	3,3	3,9
RISE	13-8-2	2,4	2,8-3,2	4,0-4,4	4,4-5,2

Integration with the electrical grid

With the rising electricity production from intermittent sources such as wind and solar power, and the decommission of base power, new challenges have arisen in Sweden. The production does not always match the consumption which makes the grid unstable and increases the demand of ancillary services. The balance between production and consumption of electricity is a prerequisite for the power system to operate reliably and to deliver electricity to the end customer.

There are big opportunities for energy services in the data center industry. The impact a data center has on the power grid can be compensated by cooperating with the energy system. This is achieved by being flexible in electricity use.

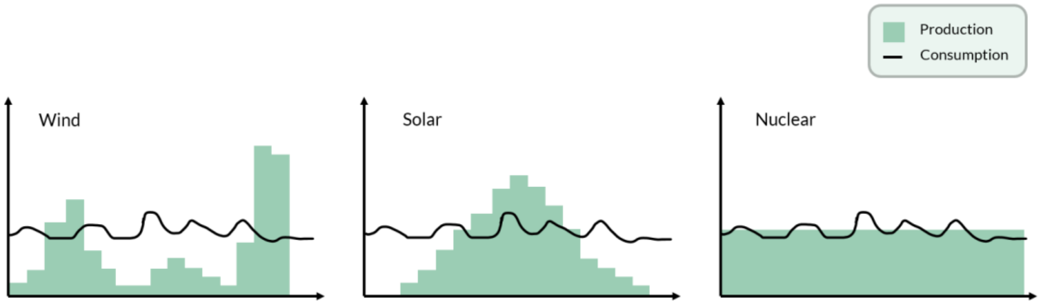

Figure 22: Illustrative production and consumption over a day from different sources.

There are different system services that can support the power grid, and here three methods of integration are explained:

- Peak shaving
- Energy arbitrage
- Ancillary services

The first two, peak shaving and energy arbitrage are methods that optimize its own operation and at the same time contribute to a stable grid.

Peak shaving

The consumption of electricity often varies over a day in a data center which can result in peaks in the consumption pattern. Peak shaving is a method where one uses stored energy, from e.g. batteries, when the power demand increases above a certain level and for a set amount of time. This to then "shave" the peaks of their electricity consumption. This method decreases the load on the power grid during peak hours.

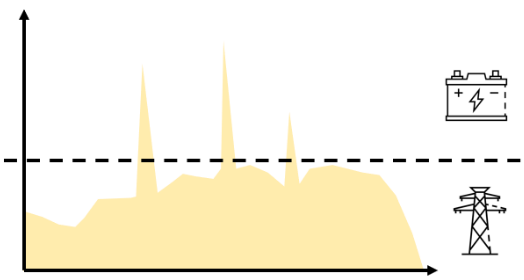

Figure 23: Illustrative consumption over a day and operations based on grid and battery.

Energy arbitrage

At the spot market the electricity price varies over the day. This variation is used in the energy arbitrage method. When the electricity is cheap it is used to charge batteries to then use the energy when electricity is more expensive, see Figure 24. One then buys electricity when there is a surplus with cheap renewable electricity. And do not burden the grid when there is a loss of electricity, with expensive often imported nonrenewable electricity.

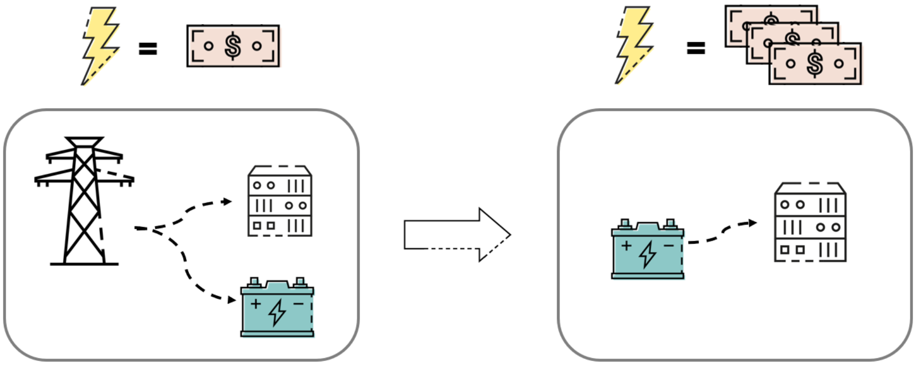

Figure 24: Energy arbitrage method.

Ancillary services

Another option is to act on the Ancillary service market to contribute to the frequency stability of the electricity grid. As mentioned, production must always match consumption to keep the frequency stable. When a deviation occurs and the frequency needs to be regulated up, either production needs to increase or consumption decrease. And this is regulated on the Ancillary market (Balansmarknaden). Here, producers and consumers put in bids of which hour per day they can be activated for the specific ancillary service.

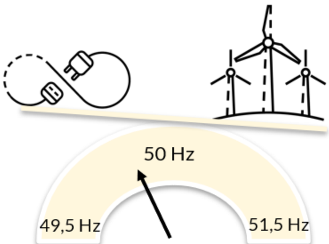

Figure 25: The Swedish power grid needs to be 50 Hz to be stable.

In Sweden there are different ancillary services with different requirements on endurance and speed, see Figure 26 below. FFR (Fast frequency reserve) and FCR-D (Frequency Containment Reserve - Disturbance) are the services that are suitable for data centers due to the duration and activation time frame. FFR is activated within 1 sec with a duration time of 30 sec. For FCR-D, 50 % is activated within 5 sec and 100 % within 30 sec. The duration time is 20 min.

For FCR-D, where the D stands for disturbance, two services are available, up, and down regulation. The down regulation is a new service that has been introduced in 2022 to stabilize the frequency when over-frequency disturbance occurs, e.g., when a lot of consumption suddenly disappears in the power system or an error on a DC connection. The amount of production must then temporarily decrease in the power system, or the amount of consumption must increase. Situations with over-frequency disturbance have previously been rare in the Nordic power system but is expected to increase as more and bigger DC connections is built and big consumption facilities are established. (Svenska Kraftnät, 2021)

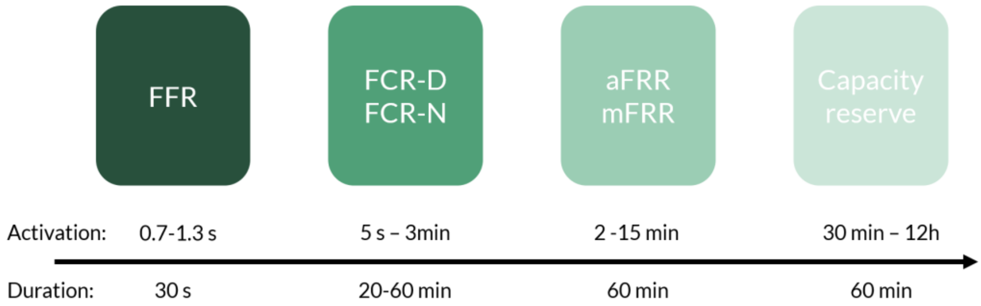

Figure 26: The available ancillary services in Sweden.

From a consumer and data center perspective, represented as a flexibility asset, being active on the ancillary market means shutting down servers (FFR and FCR-D up regulation) or consuming more power (FCR-D down regulation). An example of down regulation could be to run low priority workloads or lower the temperature in the data center. One of the requirements to act on the ancillary market for FFR and FCR-D is that the minimum bid size is 0.1 MW. On Svenska Kraftnät's webpage, more information about the requirements can be found. (Svenska Kraftnät, 2022)

The data center's potential and future services
The potential for data centers to contribute with energy services is significant. They have a workload that can increase or decrease fast, be paused, or even moved to a different data center. But the potential can depend on what type of data center there is. For example, a colocation data center has Service Level Agreements (SLAs) and tier levels towards their customers which impose the downtime that they can have.

Data centers also have Uninterruptible Power Supply (UPS) systems to be able to run critical load in case of a power outage. These often consist of batteries or flywheels and the size of it depends on how long downtime the data center should manage. The UPS power could be used for energy services depending on the data center's tier level. It could also be built out, with more batteries for example, to both cover the downtime and energy service capacity.

Svenska Kraftnäts cost for ancillary services is expected to increase in the coming years and thereby an increase in the demand. For example, FFR is expected to increase from 20 million SEK/year in 2020 to ca 60 million SEK/year which is a consequence of continuous decrease of rotational energy in the Nordic power system. (Svenska Kraftnät, 2021)

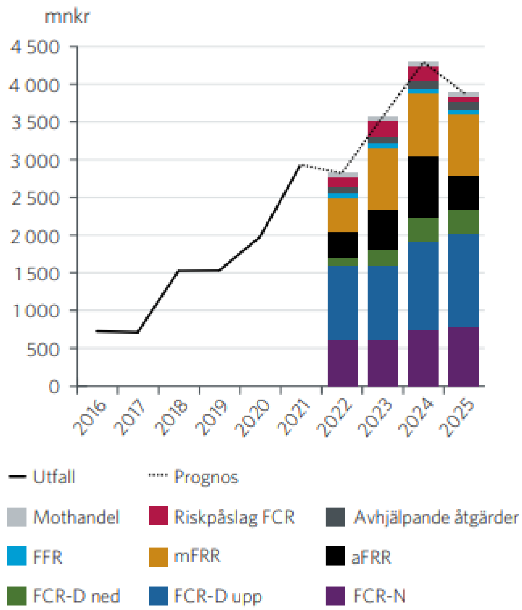

Figure 27: Svenska Kraftnäts cost for ancillary services (Svenska Kraftnät, 2021).

Due to the future power challenges and to assure the delivery dependability, a new balance model for the Nordic is under development in a joint Nordic project, Nordic Balancing Model (NBM). (Nordic Balancing Model, 2022). This requires development of operation processes, business processes and IT-system for all parties involved. Which will result in an increase in information flow that demands an increased digitalization. (Svenska Kraftnät, 2022)

Industrial symbiosis based on excess heat

Excess heat is one of the drivers for Industrial and Urban Symbiosis (IUS) which can be categorized into high- and low-grade heat, where the low-grade heat is more challenging to use and implement compared with the high-grade heat. Almost every industry is generating excess heat where data centers are known for their low-grade excess heat. Low-grade excess heat is not a new phenomenon. Data centers are known for low grade heat since it is produced in large amounts and at the same focused point compared with other process industries where heat is generated everywhere along a process line.

At RISE ICE data center work has been done scanning different possible applications for utilization of data center excess heat, resulting in a matrix showing various alternatives depending on whether the data center is air- or liquid-cooled (Figure 28). The matrix is based on the idea to use the excess heat as it is and avoiding the use of additional heat pump power for upgrading the heat, which is in favor of application utilization in areas where there is a power shortage.

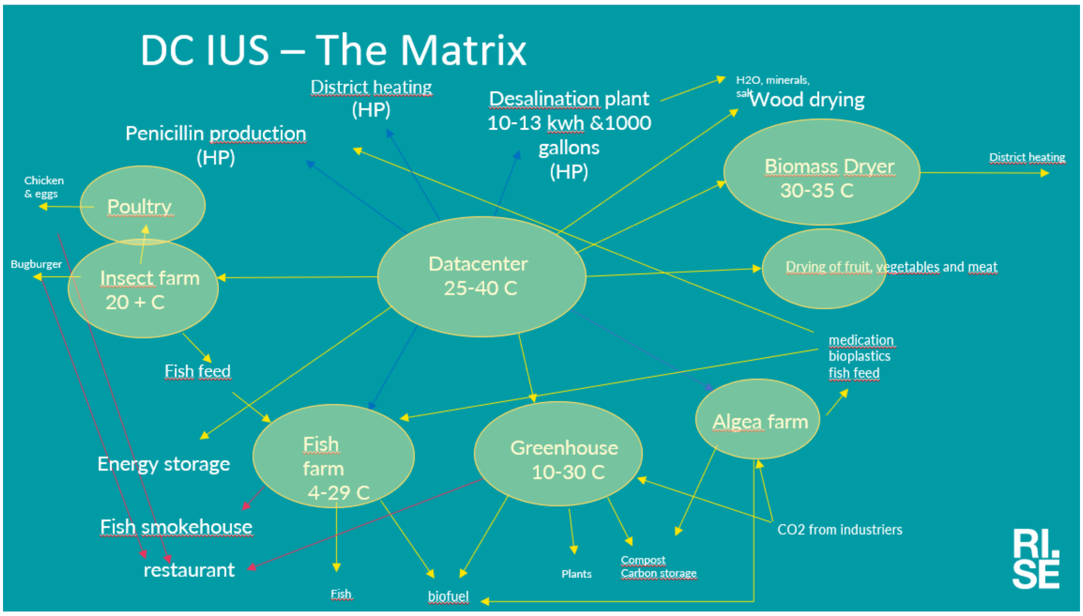

Figure 28: A matrix developed at ICE data centre for possible excess heat utilizations based on direct fresh air (yellow lines) and in liquid phase (blue lines).

The data center has great potential to be the driver for both industrial and Urban Symbiosis, below are a few examples of applications that are currently operating or in the planning stage:

- District heating: Stockholm data center parks together with Stockholm Exergi, Glesys together with Falkenberg Energy, Binero Group together with E-on (Vallentuna) are supporting local district heating systems with heat by using 2 to 3 stages of heat pump steps.
- Direct heating: HIVE is in Robertsfors heating a building area in a former diamond factory, T.Loop has contracted the first site in the region of Stockholm where the heat will be integrated with the building heating and tap water system.

- Industrial applications: ICE data center is heating a small greenhouse in the lab and Genesis Digital Assets a 300 m^2 Greenhouse in Boden. ECO data center in Falun is drying sawdust for pellet manufacturing. HIVE and Agtira has made a declaration of interest for building an aquaponic system in Boden.

The new energy efficiency directive from the EU will motivate the data center owner to utilize their excess heat into some application creating the next generation of data centers. Which use case of excess heat that is most suitable depends on the local conditions such as nearby industries or buildings.

Environmental impact – There is more to sustainability than energy efficiency

Life Cycle Assessment of data center's environmental impact
There is more to the environmental impact of data centers than energy efficiency. A commonly used approach to assess environmental impacts is to make a Life Cycle Assessment (LCA), which is a methodology associated with all the stages of the life of product or service Figure 29. For instance, in the case of a manufactured product, environmental impacts are assessed from raw material extraction and processing (cradle), through the product's manufacture, distribution and use, to the recycling or final disposal of the materials composing it (grave).

When electronic products are discarded, they are considered as e-waste and is the fastest growing worldwide waste stream by 2022 hitting 59,4 million tones corresponding to about 5980 Eiffel towers (The Roundup, 2021), all this due to the rapid changes in the technology, type of media, reduced prices, and planned obsolescence. To address the e-waste issue, the EU commission has adopted several directives for restricting the use of hazardous materials and measures to secure the ecosystem and human health by impacting the generation of e-waste. The EU directive 2012/19/EU specifies for ten different user categories the minimum level for e-waste being recovered and prepared for re-use and to be recycled, ranging from 75 to 85% that will be recovered and 55 to 80% that will be prepared for re-use and recycled.

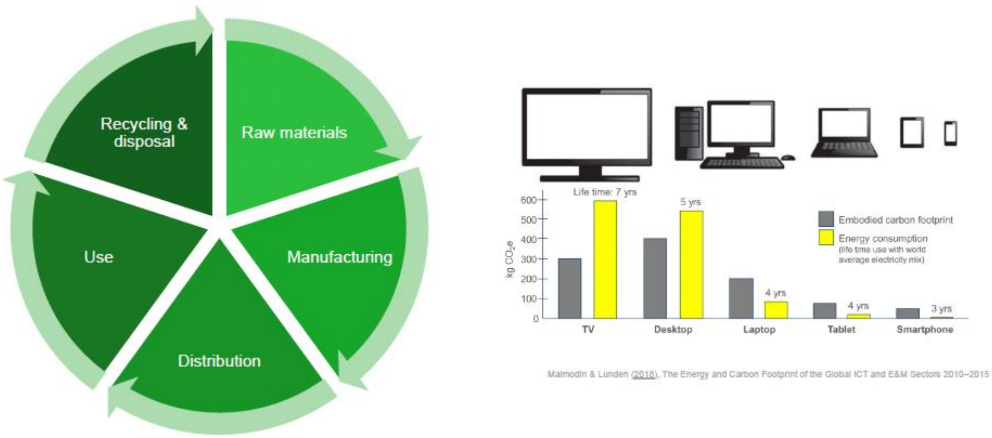

Figure 29: There are environmental impacts beyond energy use and GHG emissions throughout the product lifecycle, including impacts on soil, air water, biodiversity, and electronic waste (Malmodin, 2022).

Depending on the system boundaries the assessment can be made in three levels, scope 1 to 5 accordingly to show in Figure 30 below and as below:

Scope 1 – All Direct Emissions from the activities of an organization or under their control. Including fuel combustion on site such as gas boilers, fleet vehicles and air-conditioning leaks.

Scope 2 – Indirect Emissions from electricity purchased and used by the organization. Emissions are created in the energy production and eventually used by the organization.

Scope 3 – All Other Indirect Emissions from activities of the organization, occurring from sources that they do not own or control. These are usually the greatest share of the carbon footprint, covering emissions associated with business travel, procurement, waste, and water.

Scope 4 – which is not implemented and accepted for wide use, but focus is to support climate solutions that have positive climate impact by calculating avoided emissions, which can be defined as reduction that occurs outside of a product's life cycle or value chain but as a result of the use of that product.

Scope 5 – is still in the initial discussion stage with the aim it to introduce carbon capture in the life cycle calculations, with that can the emissions be reduced and, in some cases, even negative.

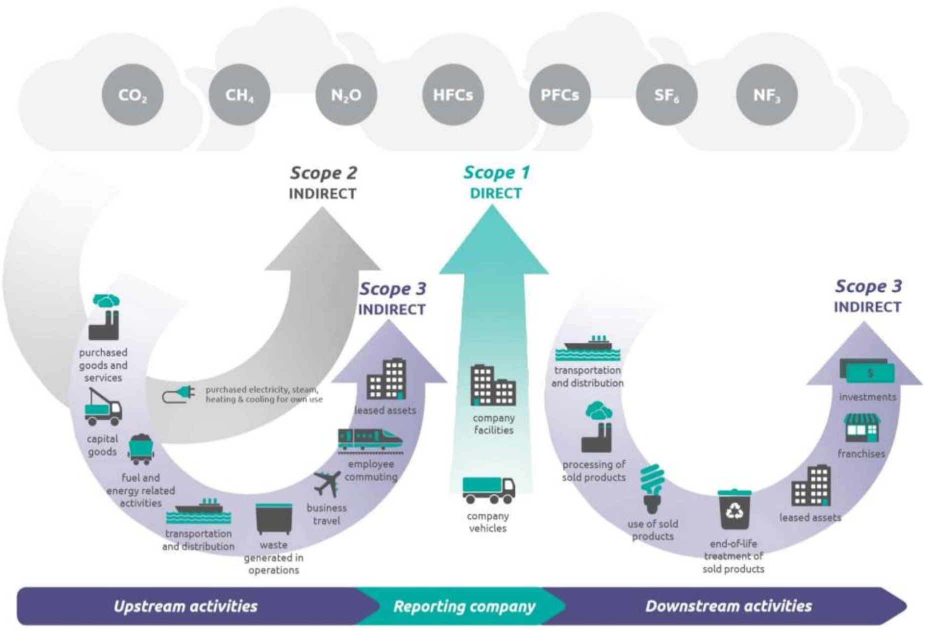

Figure 30: System boundary for scope 1 to 3 for the field of Life Cycle Assessment (OneClick LCA, 2022).

Data center's total environmental impact

The result from an LCA can be addressed as number of carbon dioxide equivalents, but the total environmental impact is still not considered. By making a full LCA further aspects are considered such as the effect on land- and water usage, which is normalized and weighted into a single score.

Through coupling LCA and Agent Based Modeling (ABM) there is the opportunity to explore the influence behavior, which is a bottom-up modeling framework and suited to explore the environmental effect of different behavior and choices. ABM can be used by a data center owner to understand and see how the environmental impact is affected for various operation strategies (behavior) and among different hardware's (choices).

Making a LCA is often time consuming and most time is used to state the material compositions and of which quality and quantity, for each product to find the right person with the right competence is often hard and some time the compositions cannot be reviled. From 1st of January 2022 the law of climate declaration of new built buildings was introduced, resulting in that building material must declare its carbon dioxide emission per kg of building material.

An Environmental Product Declaration (EPD) is an external verified standard of a material or products environmental profile across its lifetime, an EPD is objective and based on international accepted and validated methods for life cycle assessments but requires product category rules (PCR) to be in place as the template for the relevant products. Introducing EPD for products in the field of data centers will be a great help in carrying out LCA and agent base modeling, by that it will be more obvious and easier to show data center owners how different behavior and choices will affect the emission to the environment.

Key Performance Indicators of data center's environmental impact

For evaluating different types of environmental impact of data centers several metrics have been developed, where some of them are strictly defined by an ISO-standard and below are examples of used key performance indexes (KPI):

- Data Centre Infrastructure Efficiency (DCiE)
- Carbon Usage Effectiveness (CUE) [ISO/IEC 30134-8]
- Water Usage Effectiveness (WUE) [ISO/IEC 30134-9]
- Power to Performance Effectiveness (PPE)
- Power Usage Effectiveness (PUE) [ISO/IEC 30134-2, EN 50600-4-2]
- Energy Reuse Effectiveness (ERE)
- Energy Reuse Factor (ERF) [ISO/IEC 30134-6, EN 50600-4-6]
- Energy Efficiency Ratio (EER)
- Coefficient of Performance (COP)
- Data Centre Energy Productivity (DCeP)

For the operation of a data center a selection of metrics can be used to make an evaluation of the performance, below (Figure 31) is a summary of the most used KPIs by the data center owners made by the uptime institute (Uptime Institute, 2022).

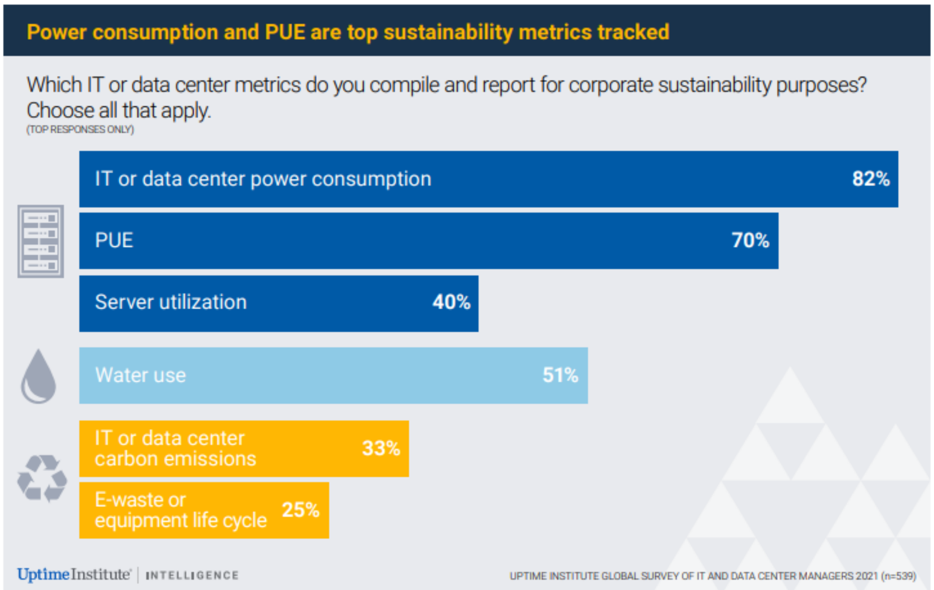

Figure 31: Most used metrics in reporting by data centers.

Technology development for data centers of the future

Power densities in data centers

The demand for data storage, computation resources and digital services is ever increasing, and as a result the number of data centers are increasing, as well as their power densities. Until ground-breaking technologies, such as quantum computing, reversable logic and neuromorphic computing reaches a technology readiness level and economic feasibility for mass deployment, the expectation is that the energy demand for data centers will continue to grow.

The power densities in CPU/GPU/Asics/xPUs will continue to increase, which will require more sophisticated cooling methods to be able to reject the heat and maintain servers within operational boundaries, see also the historical development of microprocessor power density (measured in watts per square cm) development in Figure 32, and some of the most recent process power densities listed in Table 5.

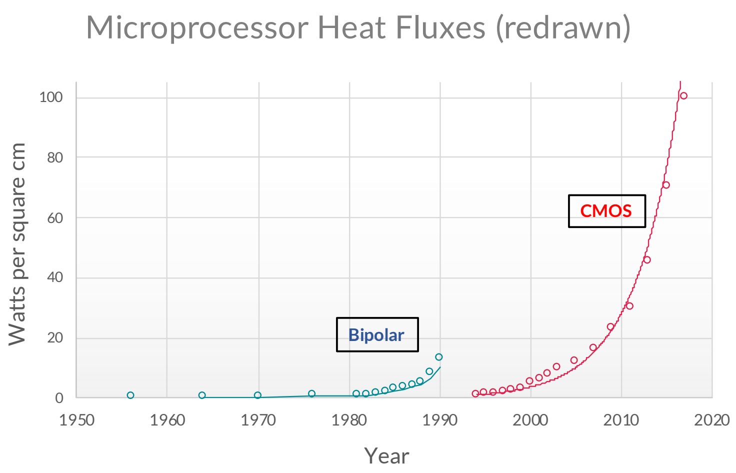

Figure 32: Power density in microprocessors. Going from Bipolar technology to CMOS made a huge difference in the early 90s. Until a new ground-breaking technology is developed, efficient cooling is becoming increasingly important. (Roger R. Schmidt, 2005)

Table 5: Power density of some modern microprocessors.

Microprocessor	W/sq.cm
AMD Vega 10	43.39
Nvidia GP102	53.08
Nvidia GV100	30.67
Intel Xeon Plat 8180	29.37
AMD Epyc	23.44
Qualcomm Centriq 2400	30.15

Air cooling of data centers

With rack densities reaching above 50kW in extreme cases, using air as the cooling medium becomes impractical, as very high airflows are required to cope with the produced heat (Miller, 2019). Air is from a thermodynamic point of view a very bad cooling fluid, as it has a low density and a low specific heat capacity. Air is mostly considered a thermal insulator, and not a conductor. However, air is a very convenient and "hassle-free" medium, that allows concurrent maintenance and easy service of data centers. The development of air-cooled data centers has come a long way over the last decades, much due to air containment installation that has become more or less standard, and better planning of IT deployment and general design of the white-space area. Using well-contained installation where hot and cold air is separated, highly efficient data centers can be achieved.

To further optimize the efficiency in air-cooled data centers, system-wide control of the data center is required. Today data centers have several independent control systems, that often act with their own interest, causing sub-optimization and energy waste.

Recent studies show that there are energy savings to be found, by interconnecting the facility control system with server internal fan control to optimize air movement, and balance air distribution. One important fact to remember is that a larger fan "always" is more efficient than a smaller one, meaning that facility fans most of the time should be prioritized over server fans. (Sarkinen, Brännvall, Gustafsson, & Summers, 2020)

Different control strategies depending on available cooling methods/prices and the possibility to sell the residual heat will become increasingly interesting in the future. It has been shown that a cold server consumes less power than a hot server, as the fans can operate at a slower speed and losses in the silicon is lower at lower temperatures providing it adheres to the ASHRAE guidelines. However, to produce a cold environment for the servers usually comes with a high price, as chillers need to bring down the temperature further. But in cases when low temperature cold is available, there is a good point of using it, examples could be free cooling at low ambient temperatures, and cheap district cooling.

On the other hand, if the waste heat streams from the data center can be used (or sold), if delivered at a high temperature, the ideal operating point from a business point of view should be much higher (CPU temperatures close to the dimensioned max temperature). The strategies on how to optimally control the data center will continue to develop, and slowly move away from the PUE-metric that has been the de facto standard for the last decade. (Jin, o.a., 2022)

Liquid cooling of data centers

To further enable higher grades of heat recovery, the temperature at the core of computing elements needs to be better maintained throughout the heat rejection (cooling) system. Since liquids in general have much better thermal performances than air, the option of using a liquid for transferring the heat is very appealing. There are today two dominating methods of using intrusive liquid cooling for servers,

1. **On-chip cooling**, where water (or other cooling media) is brought to the CPU by pipes/hoses to a heat exchanger mounted on the CPU, see Figure 33 for a picture of server prepared with direct-to-chip cooling. The heat generated in the CPU is directly (primarily by conduction) transferred to the heat exchanger, where the liquid transfers the heat away from the CPU and server. This technology has great thermal performance and has demonstrated heat rejection temperatures above 60degreesC at favorable conditions. However, the system needs to be assisted by an air-cooling system to remove the heat from other heat-generating components.

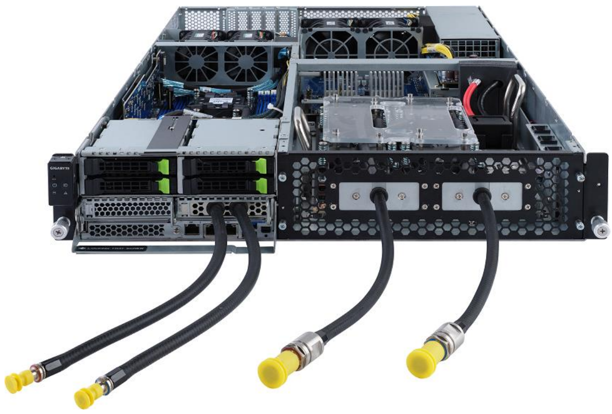

Figure 33: Server prepared for on-chip cooling.

2. **Immersion cooling**, where the complete server (or electronic device) is submerged in a non-conducting dielectric fluid. This enables heat produced by all components on server to be recovered, however, since some components does not allow for operation at as high temperature as the CPU (which typically consumes most power), the upper temperature limit must often be limited to below 60 degrees C. In Figure 34 an immersion system can be viewed.

Figure 34: Immersed servers in a non-conducting dielectric fluid.

Looking at the future, combinations of the above-mentioned technologies is highly probable, where air-cooling, immersion and on-chip is used in smart combinations to spiral up the temperature of the waste heat streams. OVH-cloud has recently published an integrated solution of immersion and on-chip cooling (OVHcloud, u.d.)), and also Asperitas has published a whitepaper indicating development in the same direction (Brink, 2019).

If other heat generating equipment exists on-site, such as compressors in refrigeration systems, electronic production through fuel cells, or transformer stations, these could also be linked to the heat recovery system to maximize the temperature of the waste heat streams.

Development of edge data centers and other technologies

Latency requirements on IT-services are increasing, and with 5G being implemented and 6G under development, further latency improvements in the communication networks are underway. To utilize these technologies fully, back-end compute infrastructure needs to be deployed closer to the end users to avoid latency in the networked internet. This will push small scale "edge"-style data centers into urban areas, where the operational challenges for data centers are very difficult due to, footprint limitations (there is little space), power constraints (there are very limited amounts of power in cities), noise constraints (increasing noise in urban areas is not welcomed), heat recovery integration challenges (the heat need is nearby, but the integration aspects are tricky). These challenges will enforce the development of small-scale edge to integrate new technologies, like immersion cooling, on-site photovoltaics, and fuel cells.

With an increasing share of power originating from non-plannable power sources, and a continuous electrification of the society, the price of power might increase, and the availability of power might decrease for period of times, hence the importance of reducing distribution and conversion losses in the power systems is becoming more important than ever. Innovative solutions, able to provide uninterrupted power both AC and DC at different voltage levels will probably gain interest during the coming years. These systems must also to a higher degree be prepared to integrate with grid flexibility services such as FFR and energy arbitrage functionality.

On-site power production is another up-and-coming approach to ensure stable power availability. In regions, where there are gas-networks available, on-site power production using fuel cells is gaining more and more interest in the industry, both for prime-power usage, and backup purposes. Combinations of electrolyzer, hydrogen storage and fuel cells are other approaches that is becoming interesting to meet the more long-term power availability fluctuations for some of the major data center operators.

Innovations in the Swedish data center industry

Due to the increased interest in the Nordics for data center operations, the Swedish data center industry sector has experienced a revitalization. Service demands from local Swedish cloud and co-location providers to end-users from other countries has increased. Product and consulting companies active in the industry sector have seen an increased demand both in the Swedish market but also world-wide. A still small but leading research and innovation activity by RISE and LTU has stimulated the industry to collaboration and new thinking (RISE Research Institute of Sweden, 2022). New knowledge and competence have been developed in partnership. An industry association with growing membership numbers, currently at 50 members, has been established, see Figure 35 below (Swedish Data Center Industry, 2022).

Figure 35: The membership chart of Swedish Data Center Industry Association.

Many new innovations and products have been developed the last 5 years by Swedish companies and organizations due to the increased interest and demand. Heat recovery for various areas of application has been developed. Several energy providers and data center operators are partnering for excess heat recovery in district heating networks, for example Stockholm Exergi, Stack and Banhof. A few data center operators have partnerships with larger greenhouse operators and are in trial phases, for example EcoDC. Frequency ancillary services have been trialed by a few and a separate company for battery-based frequency grid support has spun out of data center operator. Vattenfall and Microsoft have developed 24/7 secured supply of renewable energy. A few start-ups are focusing on Industrial symbiosis of data centers and greenhouse containers. One start-up T.Loop has based its solution on heat recovery by design.

In the cooling area of data centers Sweden has several product companies like Systemair, Swegon, SEECooling and AIA industries. Several various compact direct/indirect air/water cooling systems have been developed and improved by the companies. A new cooling strategy has been developed by RISE called holistic cooling control. Also, a self-draft cooling solution with chimney and a liquid cooling container has been developed by Swegon and RISE. In another collaboration project Eltek, ENOC, Systemair, Ericsson and RISE have developed new types of integrated edge nodes.

Other specific areas are data centers built with wood constructions with EcoDC and Hydro66 as front runners. DC power distribution is a Swedish area of strength due to experience from the Telecom industry. Comsys is a leading small company and both Vertiv and Eltek as larger companies having the DC development in Sweden. With the growth of liquid cooling CEJN has developed a product for pipe connections for smart plenums. One start-up from Chalmers is focusing on replacement of cooling paste with graphene pads for liquid cooling. A newly started company based out of KTH has products for water treatment of gray water for cooling based on the residual heat from data centers. Another small company has developed fluid based on nanomaterials to be used in liquid cooling. Another area of innovation is software-controlled solid-state switches/inverters by Blixt, a start-up in Stockholm.

EU´s vision Digital decade

The European commission published the 2030 Policy Program “Path to the Digital Decade” in September 2021. The program aims to ensure that the EU achieves its objectives and targets towards a digital transformation of our society and economy and promoting inclusive and sustainable digital policies. It set out the digital targets that the Union is expected to achieve by the end of the decade. The digital targets are based on four central points seen in Figure 36 below (European Commision, 2021).

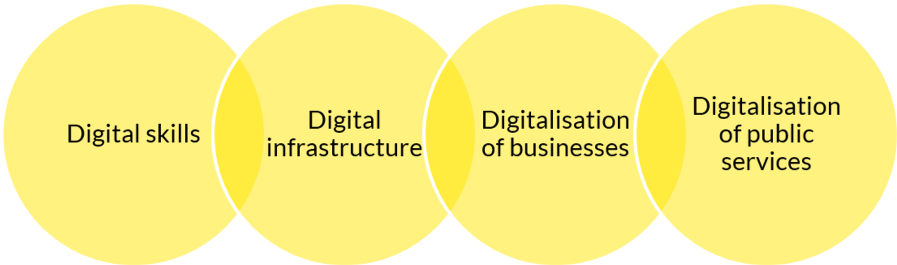

Figure 36: Four central points that the digital targets are based on (European Commision, 2021).

Below, a collection from the digital targets in the program is presented. The program brings up the importance of digital skills, basic and advanced, to reinforce the collective resilience as a society. This shows in one of the digital targets where

- 80% of those aged 16–74 should have at least basic digital skills.

The digital transformation of business is emphasized by

- at least 75% of the Unions enterprises should have cloud computing services, artificial intelligence, and big data
- Union Small and Medium Enterprises ('SME') reach a basic level of digital intensity.

A secure and sustainable digital infrastructure is of importance where it is stated that by the end of the decade all European households should be covered by

- a Gigabit network and all populated areas covered by 5G.
- a minimum of 10 000 climate neutral highly secure edge nodes should be deployed in the EU and distributed to give access to data services with low latency.
- a computer with quantum acceleration should be implemented by 2025, to make a start for the Union to be at the cutting edge of quantum capabilities by 2030.

EU Energy efficiency directive and EU Code of conduct

With the European Green Deal, the EU is increasing its climate ambition and aims at becoming the first climate-neutral continent by 2050. The Commission has therefore revised the Energy Efficiency Directive (EED), together with other EU energy and climate rules, to ensure that the new 2030 target of reducing greenhouse gas emission by at least 55% (compared to 1990) can be met (European Commission, 2022).

Because of this, the European Commission is looking at measures to improve the energy efficiency and circular economy performance. It has been estimated that digital technologies account for between 5 to 9% of global electricity use and more than 2% of global greenhouse gas emissions. This is likely to increase with digitalization and emerging technologies such as artificial intelligence, the Internet of Things and blockchain. This may lead to problematic increases of greenhouse gas emissions if no proper action is taken. Therefore, the topic of energy-efficient data centers has become a priority for the EU. Data centers must become more energy efficient, reuse waste heat, and use more renewable energy sources to achieve the 2030 climate target plan. As a conclusion, the EU Digital Strategy 28 announced a commitment to make data centers climate-neutral by 2030.

The EED recast, requests that by 15 March 2024 (for data collected in 2023) and every year thereafter that data centers operating an installed IT power demand of at least 100kW makes publicly available the information set out in Annex Via (European Commision, 2022). The set of information referred to in the EED is based on the part 4 EN50600 series of standards for data center operational efficiency key performance indicators.

To meet this goal, the Commission will further rely on a mix of existing instruments, reviews of existing legislation and new initiatives, for example:

- the Ecodesign Regulation on servers and data storage products
- the EU Code of Conduct on Data Center Energy Efficiency
- the EU Green Public Procurement criteria for data centers, server rooms and cloud services
- the Carbon Border Adjustment Mechanism

The EU Code of Conduct has been developed in response to the increasing energy consumption in data centers and the need to reduce the related environmental, economic and energy supply security impacts. This Best Practice supplement to the Code of Conduct is provided as an education and reference document as part of the Code of Conduct to assist data center operators in identifying and implementing measures to improve the energy efficiency of their data centers (Acton, Bertoldi, & Booth, 2022).

Until 2023 the European Code of Conduct for data centers and the Climate Neutral Data Center Pact have been voluntary. But with the new (16^{th} November 2022) Corporate Sustainability Reporting Directive (CSRD) (The European Parliament, 2022), companies will be required to report according to CSRD January 2024 (for the 2023 financial year). This means that preparations for what data needs to be captured and how, must happen before the end of 2022. The new directive will be the first mandatory sustainability reporting framework with which EU data center investors, operators and users must comply.

Aligned with the EU Taxonomy for Sustainable Activities, the CSRD will require companies to report on how their business activities impact both people and the environment. Moreover, "CLC/TR 50600-99-1: Information technology - Data center facilities and infrastructures: Recommended practices for energy management" best practice had been developed in parallel with EU Code of Conduct on Data Center Energy Efficiency to ensure that efficiency improves in data center applications.

The companion best practice on environmental sustainability, "CLC/TR 50600-99-2: Information technology - Data center facilities and infrastructures: Recommended practices for environmental sustainability" will be key to help the industry take steps to more sustainable activity.

The Commission is currently conducting a study to address the lack of commonly accepted definitions and methods to assess the energy efficiency, climate-neutrality, and overall sustainability of data centers: 'Greening cloud computing and electronic communications services and networks: towards climate neutrality by 2050' (European Commission, 2022). In fact, the full EN 50600 series of standards are being considered as a supporting mechanism to achieve the objectives for data centers.

The EU also adopted the Carbon Border Adjustment Mechanism which will put a carbon price on imports which cannot meet the criteria defined by the Climate Action of the EU. This mechanism aims to contribute to a global emissions reduction, instead of pushing carbon-intensive production outside Europe. It also aims to encourage industry outside the EU and our international partners to adopt ambitious climate actions.

Additional sustainability initiative

Data center operators are committed to the European Green Deal, achieving the ambitious greenhouse gas reductions of the climate law, and leveraging technology and digitalization to achieve the goal of making Europe climate neutral by 2050. To ensure data centers are an integral part of the sustainable future of Europe, data center operators must take necessary actions to make data centers climate neutral by 2030.

The Climate Neutral Data center pact main purpose is to administer the Climate Neutral Data Center – Self Regulatory Initiative, by promoting and advancing the sustainability of cloud computing, data centers, and the technology necessary to support a climate neutral digital future. The Pact works collaboratively with trade associations and data center operators that have signed the Initiative and other industry stakeholders, in the fields of Energy Efficiency, clean energy, water, circular economy, circular energy system and governance. The Pact coordinates communications between the signatories of the Initiative and the European Union. Their major thrust has evolved to engage with the EU on an appropriate level of data center monitoring both from the EED and CSRD. (Climate Neutral Data Centre, 2022)

The Sustainable Digital Infrastructure Alliance (SDIA) is the systems coordinator for the digital sector, a collaborative platform for the entire value chain to come together and solve the barriers to a sustainable digital economy. SDIA unlocks collaboration across the entire ecosystem, the Alliance is guided by an independent roadmap with the areas of emissions, energy consumption, electronic waste, resource consumption, pollution, and socioeconomic advocating transparency as the foundation of sustainability. (SDIA, 2022)

The iMasons Climate Accord is a consortium of companies agreeing to an open standard and governance to report carbon impact in materials, products, and power across digital infrastructure. The Digital Infrastructure Maturity Model is a standardized framework used to measure progress in reducing embodied carbon in materials used to build data centers, embodied carbon of products deployed in data centers, and the hourly carbon intensity of source power used to operate data centers. The goal is global carbon accounting for each unique data center location over its lifetime which is done through the four areas: power-, materials-, equipment- and the maturity model work group. Participating companies will support a carbon label schema for products and data center buildings in conjunction with source power carbon-intensity tracking. (Climate Accord, 2022)

Future work

Future work in the area of monitoring the development of data centers, its technologies and energy use, is to assess it over a longer time period including a survey as an assignment from the government. The task could be as a preparation for the coming EU directive on reporting and data collection of metrics from the data center industry. The national data center industry association could be involved in the information campaign and evaluation.

Another future work of importance and that is urgent, is to develop and write a strategy for the data center industry in Sweden. There is a need to carry out government initiatives around data centers and connect it with the goals in the Swedish business and energy policies. Part of that is to develop a roadmap for investments in R&D for efficient next-generation computing and telecommunication data center infrastructure technologies.

Conclusions

The conclusion is that the growth of energy use in data centers is strong in Sweden and the absolute level will be essential by 2025 and beyond, but still not at the dramatic levels mentioned by the uninitiated. Many hyperscale data center operators are establishing in Sweden and workloads are moving from Europe driving the demand. RISE assesses that the current energy use by data centers in Sweden is 2,8–3,2 TWh per year in 2022 and that the estimated energy use will be 4,0–4,4 TWh per year by 2025. Beyond 2025 there are many uncertainties, and the estimate is 4,4–5,2 TWh per year by 2030.

The conclusion is also that this is an important industry for Swedish technology advancements, the digitalization and green transformation. Digital services, like telecom, media, AI, and automation that are hosted in data centers, are vital and necessary for the Swedish society and industry and the data center sector is hence very important for Swedish sovereignty and technology leadership. Research and innovation are key ingredients for continued improvements of energy efficiency, operations performance, and energy system integration. (European Commision, 2022)

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Team RISE

ICE data center is part of Sweden's largest research institute RISE and is the leading research group with the largest open research facility for data centers in Europe. ICE stands for Infrastructure and Cloud research & test Environment and is a test bed with a focus on digitization, digital systems and IT infrastructure. The center coordinates national research projects as well as testing and development of all functions in the technology stack; the infrastructure and construction of data centers, edge and cloud applications, IT architecture and machine learning. ICE's mission is to put Sweden at the forefront in the field of energy-efficient data center solutions, sustainability for IT infrastructure, edge computing, cloud applications and data analysis. RISE can offer consulting support with both breadth and depth to carry out the mission regarding energy use in data centers and digital systems.

Task leader was Tor Björn Minde is currently manager of RISE ICE Data center. The implementation team included Jeanette Petersson project manager, Tina Stark junior researcher, Jonas Gustafsson doctor and senior researcher and Mattias Vesterlund doctor and senior researcher. Quality assurance was Jon Summers professor and scientific leader in data centers at the Swedish Research Institute.

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