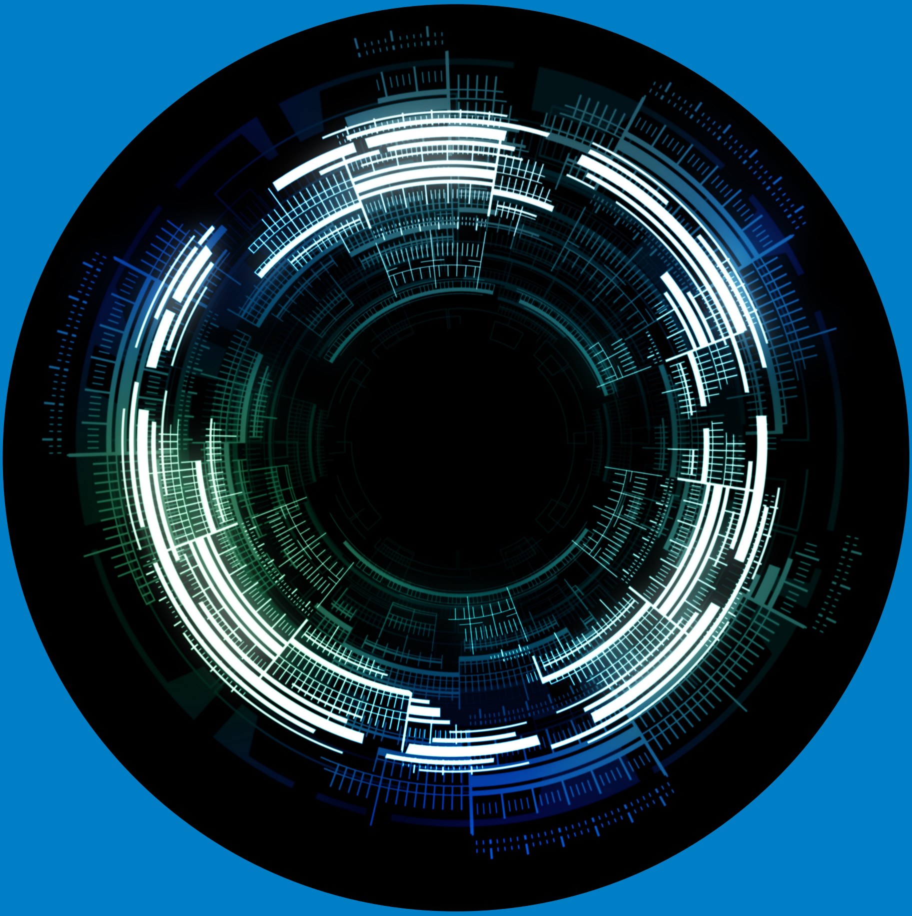
Department of Communications and Networks

# Towards Sustainable Data Centers and ICT Services

**Matti Pärssinen**



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# Towards Sustainable Data Centers and ICT Services

**Matti Pärssinen**

A doctoral dissertation completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Electrical Engineering, at a public examination held at the lecture hall AS1 of the Maarintie 8 building on 23 August 2019 at noon.

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# Abstract

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**Abstract**

According to the Intergovernmental Panel on Climate Change report in 2018, the current rate causes global warming of 1.5 °C between 2030 and 2052. Despite the positive impacts of dematerialization, decarbonization, and demobilization, there is a growing concern on the environmental impact of ICT. Can services moving online be considered sustainable development? Favorable and adverse environmental impacts can be found on all system levels. There is a possible rebound effect; even though the energy efficiency of devices has improved, the scale of use has increased at a rate which results in an increase in the total energy consumption.

There are two ways to reduce ICT energy consumption: 1) improve the energy efficiency of the devices and 2) make ICT services consume less resources and energy. This thesis assesses the energy consumption of the ICT infrastructure and gives case examples of both options of consumption reduction. The first case examines reusing of waste heat emerging from data centers (DCs), and the second case focuses on reducing ad fraud traffic in online advertising.

The energy efficiency of DCs is becoming more critical as their number is growing. The electricity consumed by a DC converts to heat. However, most of the heat is not utilized, even though different solutions already exist. Online advertising is associated with funding online search services, map services, and social media to billions of users, and the sustainable growth of this industry is seen as necessary. Online ads are almost indistinguishable to end-users, but consume a significant part of the resources. Online ads increase energy consumption through four factors: 1) the amount of downloaded data increases, 2) the varying inter-transfer interval reserves resources, 3) the time required to access the payload content or application increases, and 4) the amount of active connections increases.

The results of this thesis show that DCs can become more energy efficient by investing in waste heat reuse. The investment is profitable inside the full range of uncertainty in large DCs. In medium DCs, the extremely pessimistic factor values result in a negative outcome. Small DCs are sensitive to factor variations. In 2016, online advertising consumed 20–282 TWh of energy. With 2016 input factor values, online advertising consumed 106 TWh of energy. The carbon emissions were 60 Mt CO2e (between 12 and 159 Mt of CO2e with uncertainty). The share of ad fraud traffic was 13.87 Mt of CO2e emissions (between 2.65 and 36.78 Mt of CO2e with uncertainty). The thesis discussed the use of blockchains to control fraudulent advertising traffic, and concludes that blockchain can become a solution to address some of the issues of ad fraud, but the current technology is not ready.

**Keywords** Sustainability, Internet services, energy efficiency, environmental impact assessment, data center, online advertising, ad fraud, blockchain

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# Tiivistelmä

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**Väitöskirjan nimi**
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**Tiivistelmä**

Kansainvälisen ilmastonmuutospaneelin vuonna 2018 julkaiseman raportin mukaan maapallon lämpeneminen saavuttaa nykytahdilla 1.5 °C tason vuosien 2030 ja 2052 välillä. Huoli ICT:n ympäristövaikutuksista on kasvanut, huolimatta sen positiivisista vaikutuksista, kuten vähentynyt materialisaatio ja matkustaminen sekä hiilettömyyden kasvamisesta. Onko palveluiden digitalisoituminen kestävää kehitystä? Myönteisiä sekä kielteisiä ympäristövaikutuksia löytyy kaikilla systeemitasoilla. On myös mahdollinen takaisinkytkentäefekti; vaikka laitteiden energiatehokkuus paranee, palveluiden käyttö kasvaa nopeudella, jonka lopputuloksena energian kokonaiskulutus on kasvanut. ICT:n energiankulutusta voidaan vähentää kahdella tavalla: 1) parantamalla laitteiden energiatehokkuutta ja 2) vähentämällä palveluiden käyttämien resurssien ja energian määrää. Tämä lopputyö selvittää IT-infrastruktuurin energiankulutusta ja tutkii esimerkkitapauksia kummastakin tavasta vähentää kulutusta. Ensimmäiseksi tutkitaan datakeskusten hukkalämmön hyödyntämistä, ja sen jälkeen mainoshuijausten vaikutusta verkkoliikenteen määrään sekä ICT teollisuuden energian kokonaiskulutukseen.

Datakeskusten energiatehokkuuden tärkeys korostuu määrän kasvaessa. Datakeskuksissa kulutettu sähkö muuntuu lämmöksi. Tätä syntynyttä lämpöä ei kuitenkaan hyödynnetä, vaikka soveltuvia ratkaisuja on saatavilla. Verkossa tapahtuva markkinointi mielletään yleensä rahoituskeinona tarjota hakusana-, kartta-, ja sosiaalisen median palveluita miljardeille käyttäjille. Toimialan kasvu nähdään välttämättömänä. Verkkomarkkinointi on loppukäyttäjälle lähes huomaamatonta mutta kuluttaa merkittäviä määriä resursseja. Verkkomarkkinointi kasvattaa energiankulutusta neljällä eri tavalla: 1) ladatun datan määrä kasvaa, 2) tiedonsiirron vaihteluväli varaa resursseja, 3) hyötysisältöön pääsemiseen käytetty aika kasvaa ja 4) aktiivisten yhteyksien määrä kasvaa.

Datakeskusten energiatehokkuus paranee investoimalla hukkalämmön hyödyntämiseen. Investointi on kannattava isoissa datakeskuksissa. Keskikokoisissa datakeskuksissa vain erittäin pessimistiset lähtöarvot tuottavat negatiivisen tuloksen. Pienet datakeskukset ovet herkkiä lähtöarvojen vaihtelun osalta. Vuonna 2016 verkkomarkkinointi kulutti 20–282 TWh energiaa. Vuoden 2016 lähtöarvoilla verkkomarkkinointi kulutti 106 TWh energiaa ja emissiot olivat 60 Mt CO2e (epävarmuus huomioiden 12 ja 159 Mt CO2e välillä). Mainoshuijausten aiheuttaman verkkoliikenteen osuus oli 13.87 Mt CO2e emissioita (epävarmuus huomioiden 2.65 ja 36.78 Mt CO2e välillä). Lopputyö arvioi lohkoketjun hyödyntämistä mainoshuijausten aiheuttaman liikenteen kontrolloinnissa. Lohkoketjusta voi tulla käytännöllinen ratkaisu osaan ongelmista, mutta teknologia ei ole sellaisenaan valmis.

**Avainsanat** Kestävä kehitys, Internet-palvelut, energiatehokkuus, ympäristövaikutusten arviointi, datakeskus, verkkomarkkinointi, mainoshuijaus, lohkoketju

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# Preface

My vision has actualized with the publication of this thesis. I have worked with two exceptional teams on various topics, which have offered me a chance to learn lots of new concepts, both technical and non-technical.

The initial inspiration for addressing the energy efficiency in data centers came from professor Jukka Manner when we discussed possible research areas. Doctoral candidate Mikko Wahlroos contacted me and suggested we start working on a publication together. My initial study plan took a rapid turn. This co-operation turned out to be most effective, and we formed a dream team for conducting science.

While writing about waste heat utilization, I had a call from my dear friend Mikko Kotila, who suggested that we start to investigate problems concerning the online advertising ecosystem together with researchers professor Ruben Cuevas from Universidad Carlos III de Madrid and M.Sc. Amit Phansalkar from Boston. This research team addressed issues greater than I had ever imagined. We published two articles with this team of talents.

I thank my responsible professor Jukka Manner for guidance during the work. In addition, I would like to thank my second supervisor adjunct professor Suvi Haimi for all assistance, support, and guidance especially in the early phase of my writing. I want to present special gratitude to my proof-reader Mia Tähtinen from Telia Cygate Oy.

I am thankful to my pre-examiners Professor Jussi Kangasharju from the University of Helsinki and Professor Robert Basmadjian from the University of Passau for their time and effort on reviewing the thesis as well as their feedback to make the thesis better.

I thank my co-authors professor Jukka Manner, Mikko Kotila, Mikko Wahlroos, associate professor Ruben Cuevas, professor Sanna Syri, Amit Phansalkar, and Samuli Rinne for their effort to make the publications possible.

I want to name one person to receive most of my gratitude and love, my wife, Mari Suokari-Pärssinen. I am a challenging husband to live with. My projects and life-long learning creates everyday challenges. However, Mari has always supported my efforts. Our son Antto balanced, brightened and maintained confidence in me during this journey. Hopefully, this thesis serves as an example for Antto, that hard work does reward.

I am grateful to my parents Valto and Marjatta Pärssinen who have supported me all my life from the beginning of my studies in the 1st grade. In addition, I thank my brother Dr. Antti Pärssinen for his support. Special thanks to my friends Susann Rännäri, Aino Kianto, Mirva and Anssi Auvinen, Petter Byholm, Maarit Kettunen, and Sanna Ingman.

Helsinki, May 9th, 2019
Matti Antero Pärssinen

# Contents

# List of Abbreviations and Symbols

| | |
|---|---|
| ANA | Association of National Advertisers |
| API | Application Programming Interface |
| BAT | Basic Attention Token |
| CAPEX | CAPital EXpenditure |
| CDN | Content Delivery Network |
| CHP | Combined Heat and Power |
| $CO_2$ | Carbon Dioxide |
| $CO_2e$ | Carbon Dioxide Equivalent |
| COP | Coefficient Of Performance |
| CPE | Customer Premises Equipment |
| CPU | Central Processing Unit |
| CRAH | Computer Room Air Handler |
| CSF | Critical Success Factor |
| DC | Data Center |
| DCeP | Data Center energy Productivity |
| DCF | Discounted Cash Flow |
| DENS | Data center Energy efficient Network-aware Scheduling |
| DH | District Heating |
| DHW | Domestic Hot Water |
| dPOW | delayed Proof of Work |
| DSP | Demand Side Platforms |
| DVFS | Dynamic Voltage Frequency Scaling |
| DWPE | Data center Workload Power Efficiency |
| EBIT | Earnings Before Interests and Taxes |

| | |
|---|---|
| EIA | Environmental Impact Assessment |
| EMS | Energy Management System |
| ERE | Energy Reuse Effectiveness |
| ERF | Energy Reuse Factor |
| ESX | VMware Elastic Sky X |
| EU | European Union |
| FVER | Fixed to Variable Energy Ratio |
| HOB | Heat Only Boiler |
| HTML5 | Hypertext Markup Language 5 |
| HTTP | Hypertext Transfer Protocol |
| HVAC | Heating, Ventilation, and Air Conditioning |
| IA | Impact Assessment |
| IAB | Interactive Advertising Bureau |
| ICO | Initial Coin Offering |
| ICT | Information and Communications Technology |
| IRR | Internal Rate of Return |
| ISP | Internet Service Provider |
| IT | Information Technology |
| IXP | Internet eXchange Points |
| KYB | Know-Your-Business |
| KYC | Know-Your-Customer |
| LCA | Life Cycle Assessment |
| NPUE | Network Power Usage Effectiveness |
| NPV | Net Present Value |
| nZEB | near Zero Energy Buildings |
| OECD | Organisation for Economic Co-operation and Development |
| OFCF | Operating Free Cash Flows |
| PB | discounted Payback Period |
| PC | Personal Computer |
| PDE | Power Density Efficiency |
| PoA | Proof of Activity |

| | |
|---|---|
| PoB | Proof of Burn |
| PoC | Proof of Capacity |
| PoE | Proof of Existence |
| PoI | Proof of Intelligence |
| PoL | Proof of Luck |
| PoS | Proof of Stake |
| PoW | Proof of Work |
| PPW | Performance per Watt |
| PS-CORE | Packet Switched Core |
| PUE | Power Usage Effectiveness |
| PV | Present Value |
| RAN | Radio Access Network |
| RHI | Return Heat Index |
| ROA | Real Option Analysis |
| ROI | Return On Investment |
| RQ | Research Questions |
| RTB | Real-Time Bidding |
| RTI | Return Temperature Index |
| SHI | Supply Heat Index |
| SLA | Service Level Agreement |
| sPUE | system Power Usage Effectiveness |
| SSP | Supply Side Platform |
| TCO | Total Cost of Ownership |
| TCP | Transmission Control Protocol |
| ToU | Time-of-Use |
| UPS | Uninterruptible Power Supply |
| URL | Uniform Resource Locator |
| VM | Virtual Machine |
| WACC | Weighted Average Cost of Capital |
| WPE | Workload Power Efficiency |

# List of Publications

This doctoral thesis consists of a summary and of the following publications which are referred to in the text by their numerals

**I.** Wahlroos, Mikko; Pärssinen, Matti; Syri, Sanna; Manner, Jukka. 2017. Utilizing data center waste heat in district heating – Impacts on energy efficiency and prospects for low-temperature district heating networks. Elsevier. Energy, volume 140, issue 1, pages 1228-1238. ISSN: 0360-5442. DOI:10.1016/j.energy.2017.08.078.

**II.** Wahlroos, Mikko; Pärssinen, Matti; Rinne, Samuli; Syri, Sanna; Manner, Jukka. 2018. Future views on waste heat utilization - case of data centers in Northern Europe. Elsevier. Renewable and Sustainable Energy Reviews, volume 82, issue 2, pages 1749-1764. ISSN: 1364-0321. DOI:10.1016/j.rser.2017.10.058.

**III.** Pärssinen, Matti; Kotila, Mikko; Cuevas, Ruben; Phansalkar, Amit; Manner, Jukka. 2018. Environmental impact assessment of online advertising. Elsevier. Environmental Impact Assessment Review, volume 73, pages 177-200. ISSN: 0195-9255. DOI:10.1016/j.eiar.2018.08.004.

**IV.** Pärssinen, Matti; Kotila, Mikko; Cuevas, Ruben; Phansalkar, Amit; Manner, Jukka. 2018. Is Blockchain Ready to Revolutionize Online Advertising? IEEE. IEEE Access, volume 6, issue 1, pages 1-16. ISSN: 2169-3536. DOI:10.1109/ACCESS.2018.2872694.

**V.** Pärssinen, Matti; Wahlroos, Mikko; Manner, Jukka; Syri, Sanna. 2018. Waste Heat from Data Centers: An Investment Analysis. Elsevier. Sustainable Cities and Society, volume 44, pages 428-444. ISSN: 2210-6707 DOI:10.1016/j.scs.2018.10.023.

# Author's Contribution

**Publication I:** Utilizing data center waste heat in district heating – Impacts on energy efficiency and prospects for low-temperature district heating networks.

Pärssinen and Wahlroos are the main authors. The concept was planned with Pärssinen, Wahlroos, and Syri. Wahlroos conducted simulations with EnergyPRO and analyzed the results. Pärssinen measured the data center load profile and did the statistical analysis of waste heat availability. Pärssinen and Wahlroos wrote the paper, while Manner and Syri provided guidance and reviews.

**Publication II:** Future views on waste heat utilization – case of data centers in Northern Europe

Pärssinen and Wahlroos are the main authors. Pärssinen, Wahlroos, and Syri planned the concept of the paper. Pärssinen provided analysis for business cases for data center operators. Wahlroos carried out the literature review and studied current projects for data centers. Rinne provided lifecycle assessment calculations in the paper. Pärssinen and Wahlroos did the majority of the writing, while Rinne wrote the lifecycle assessment part. Manner and Syri provided guidance and reviews on the paper.

**Publication III:** Environmental impact assessment of online advertising.

Pärssinen is the main author and has written nearly the complete paper. Pärssinen created the eight-step framework for assessing the use-phase environmental impact of any Internet-related service and applied the framework for assessing the environmental impact of online advertising. Kotila contributed the definitions and characteristics of the online advertising ecosystem. Pärssinen and Kotila developed a Python-based assessment tool for future use. Kotila, Cuevas, Phansalkar and Manner provided guidance and reviews on the paper.

**Publication IV:** Is Blockchain Ready to Revolutionize Online Advertising?

Pärssinen is the main author and has written almost the complete paper. Kotila and Cuevas provided the Section *Specific Requirements Related to Online Advertising*. Chapter *Discussion* was written together with Cuevas and Kotila. Kotila, Cuevas, Phansalkar and Manner provided guidance and reviews on the paper.

**Publication V:** Waste Heat from Data Centers: An Investment Analysis.

Pärssinen is the main author. Pärssinen defined the six-stage net present value analysis methodology applied in the paper. Pärssinen created the Monte Carlo simulation Python tool for net present value (NPV) analysis and uncertainty distribution for three different sized data centers. Wahlroos simulated the district heating purchase price and electricity price statistically. Pärssinen and Wahlroos wrote the paper, while Manner and Syri provided guidance and reviews.

# 1. Introduction

According to the Intergovernmental Panel on Climate Change (IPCC special report 2018), global warming is likely to increase to 1.5 °C between 2030 and 2052 if the current rate continues [1]. In various places around the world, temperatures are rising at a rate beyond the global average. The changes in temperature are particularly hard on the Arctic, with the rate of warming ranging from two to three times the average. Reaching and sustaining net-zero global anthropogenic $CO_2$ emissions and declining net non-$CO_2$ radiative forcing would halt anthropogenic global warming on multi-decadal timescales with high confidence. On longer time timescales, sustained net negative global anthropogenic $CO_2$ emissions and further reductions in non-$CO_2$ radiative forcing may still be required. These actions are required to prevent further warming due to Earth system feedbacks, reverse ocean acidification and to minimize sea level rise [1].

Malmodin et al. (2010) study found that information and communications technology (ICT) sector produced 1.3% of the worldwide $CO_2$ emissions and consumed 3.9% of the global energy production [2]. Given the growth of ICT since 2007 and the fact that more than 80% of the population in developed countries are heavy Internet users [3], this is a growing percentage [4]. Estimates of energy intensity, kWh/GB, of the Internet, vary significantly; in literature, results ranging from 136 kWh/GB [5] to 0.0064 kWh/GB were found [6], a factor of more than 21 000. The definition of the Internet is not constant throughout literature.

Despite the positive impacts of dematerialization, decarbonization, and demobilization, there are increasing concerns about the complexity and uncertainty of the environmental impacts of ICT [7]. Another cause for concern is whether services moving online is sustainable development, rather than a burden on the environment. Favorable and adverse environmental impacts can be found on all system levels depending on the depth of causal chains and the period assumed [8].

The ICT sector is complex, interdependent, scale-dependent and contains uncertainties [4]. As a dynamic industry, it disrupts many other industries. In addition, there is a possible rebound effect; even though the energy intensity of devices has improved, the scale of use has increased at a rate leading to an increase in the total consumption of energy [4].

The world requires energy and heat and is dependent on data centers (DCs). The majority of the global population lives in urban areas and is responsible for approximately 70% of the total primary energy usage. Urbanization is expected to increase to 75% by 2030. In 2012, heating and cooling of buildings in the EU consumed 50% of the total energy [9]. Nearly all this energy is from non-renewable sources [10]. The Paris (COP21) 2015 agreement is expected to increase the use of renewable energy sources and energy efficiency activities. In addition, the EU Energy Efficiency Directive aims to reduce energy consumption.

The energy efficiency of DCs is becoming increasingly critical as the number of DCs is rapidly growing. DCs require vast amounts of cooling energy. The electricity consumed in a DC almost entirely converts to heat. However, most of the heat is not utilized, even though different solutions already exist. Global warming creates an increasing amount of cooling demand at the same time as power density per floor space in DCs is increasing, and demand for processing power is rising faster than the processing technology is advancing [11]. The size and capacity of DCs is increasing; there is a continuous increase in energy consumption and related $CO_2$ emissions [11].

There are two generic ways to reduce energy consumption: 1) improve the energy efficiency of the ICT devices and 2) make ICT services consume less resources and energy. This thesis aims to assess the energy consumption of the ICT infrastructure and to give practical case examples for both of the general ways to reduce ICT energy consumption. The case example of energy efficiency is the utilization of DC waste heat, and the case example for making ICT services consume less resources and energy is the reduction of ad fraud related traffic in online advertising.

There is a high demand for heat in the Nordic countries, and industrial waste heat is already utilized in different processes and district heating (DH) on a large scale, especially in Finland and Sweden (waste heat in DH 3.3% in 2015 in Finland [12] and 8% in 2014 in Sweden [13]). DH with highly efficient combined heat and power (CHP) is ubiquitous in Finland and Sweden.

Online advertising is a major social and economic driver of the information society. First, online advertising is associated with funding online search services, map services, and social media to billions of users. Second, the market volume of online advertising reached $72.5B in the US alone in 2016 with an annual growth rate of 22% [14]. Third, online advertising represents a source of jobs. For instance, recent studies have estimated that 0.9M (0.4%) direct and 5.4M (2.5%) indirect jobs were associated with online advertising in the EU-28 workforce in 2014 [15]. Fourth, online advertising represents a fundamental source of income of companies known for their technological innovations, such as Google or Facebook [16], [17]. Therefore, the sustainable growth of this industry is seen as necessary.

Online ads are almost indistinguishable to end-users but consume a significant part of the resources. Online advertising increases energy consumption end-to-end with four factors: 1) the amount of downloaded data increases, 2) the varying inter-transfer interval reserves network, DC, and end-user device resources, 3) the time required to access the payload content or application increases, and 4) the number of active connections from the end-user device to the infrastructure increases.

As an example of online advertising energy consumption, Aisch et al. (2015) measured, in the New York Times article (2015), the mix of online ads and editorial content on top 50 news websites, and discovered that over half of all downloaded data originates from online ads. For instance, loading Boston.com with ads and trackers had a download time of 30.8 seconds compared to the 8.1 seconds of just the editorial content without ads and trackers. In this case, online ads and trackers created 15.4 MB of data compared to the 4 MB of the editorial content. More than half of all the data come from ads and trackers [18].

## 1.1 Motivation

The motivation for this thesis is based on three challenges. Firstly, there was a need for a comprehensive framework for environmental impact assessment (EIA) of Internet services. The framework should be modular and support many layers of analysis to overcome the complexity of the Internet. The considerable variability in existing results and levels of uncertainties indicate a need for a common framework. Many of the previous studies focus on device level analysis [19]–[21] rather than the services on top of them. There are excellent research papers on methodologies of EIA [22]–[27] and case studies illustrating some of the Internet's pain points [4], [28]–[32]. The key findings from previous literature can be formed into a general framework for assessing the impact of any Internet service, including online advertising.

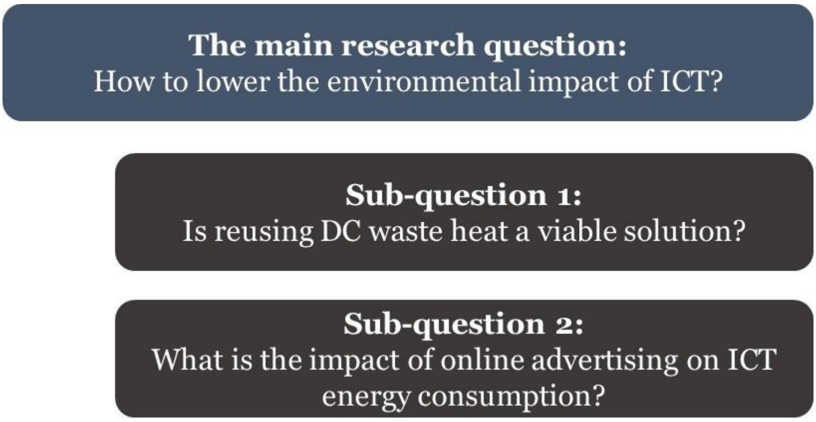
Secondly, even though there have been many studies on DC waste heat utilization, many of the projects have not been realized, as the real economic incentive has been lacking from the stakeholders. Research was needed to investigate when waste heat is available from a DC and can it be trusted as a reliable source of heat. Also, an investigation of how DC waste heat utilization affects other heat production units in a DH network was needed. An investigation was needed to verify the economic feasibility of a waste heat utilization solution.

Thirdly, online advertising promises real-time measurements, targeting, and optimization at a scale. A Dalessandro et al. (2015) study [33], demonstrated that every intention of every user is collected. Millions of ads are delivered to capitalize few purchases. A data set of 58 campaigns shows over 50% of the campaigns see less than one purchase per million ad impressions, and this is considered an excellent result in the advertising industry. A model of 50 positive cases would have to have 50 million ad impressions as proof [33]. As an example, an advertiser wanting to conduct a comparison between targeting firms requires tens of millions of ad impressions to prove the performance of each firm [34]. Everything is on a massive scale.

According to a 2012 study, 10–25% of click frauds were undetectable [34]. There are three different ways for a click-fraud to occur: 1) use of click bots, 2) tricking users into clicking ads, and 3) paying human clickers. Over 40% of mobile ad clicks are either accidental or fraudulent [34]. According to a Botlab (2017) study, based on a substantial dataset, the percentage of fraudulent online ad-impression (ad fraud) was 23% of the total online advertising traffic [35]. Research was needed to assess the energy consumption of online advertising and what would be the environmental impact of removing ad fraud related traffic.

## 1.2 Research Problem Area

The thesis answers three different topical questions related to ICT energy consumption. The main research question is how to lower the environmental impact of ICT. The two sub-questions are: 1) is reusing DC waste heat a viable solution and 2) what is the impact of online advertising on ICT energy consumption? The structure of the research questions (RQ) is presented in Figure 1.



**The main research question:**
How to lower the environmental impact of ICT?

**Sub-question 1:**
Is reusing DC waste heat a viable solution?

**Sub-question 2:**
What is the impact of online advertising on ICT energy consumption?

**Figure 1**. Main research question and sub-questions.

RQs are mapped to published articles in Table 1.

**Table 1.** Mapping of publications to research questions.

| Research Question | Publication I | Publication II | Publication III | Publication IV | Publication V |
|---|---|---|---|---|---|
| Main RQ | X | X | X | X | X |
| Sub-RQ1 | X | X | | | X |
| Sub-RQ2 | | | X | X | |

The publications can be divided into three main themes: 1) ICT energy consumption, 2) energy efficiency, and 3) ICT services consumption. Together these form a holistic way to address the research questions. Figure 2 presents publications in relation to the main themes. In addition, the scientific topical scope is elaborated in a triangle between three points-of-view: 1) methodology, 2) technology, and 3) economics.

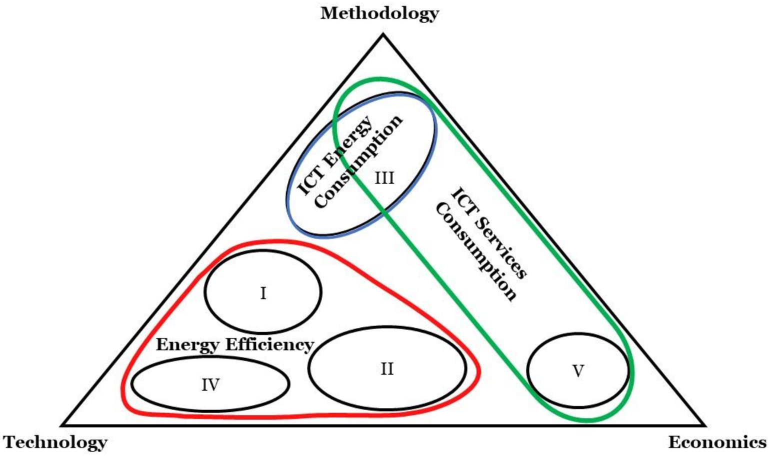


**Figure 2.** Article relations to main themes and scientific domains.

## 1.3 Contribution

### Publication I

The first contribution was an investigation of DC waste heat availability and reliability. Another contribution was a demonstration of how DC waste heat utilization affects heat production units in a DH network.

In the publication, a waste heat supply profile of a sample DC was formed. In addition, a simulation of the Espoo DH network with actual plants, operating costs, and different waste heat levels was conducted. Furthermore, waste heat utilization and the impact of pricing on heat production in a DH network were investigated.

### Publication II

The contribution of the publication included an analysis of the current solutions and technologies in existing Nordic DCs and the potential in the future. The analysis was carried out by investigating the best solutions for waste heat recovery and utilization both economically and technically in the Nordic countries. In Finland, many DCs are built close to an existing DH network. Thus it was proposed that utilizing waste heat in DH networks would be the most viable solution economically.

DH networks and DCs have different owners. Therefore, an evaluation of the pros and cons, including an analysis of who should invest in waste heat capturing was conducted. The article suggests applying an 8-step change process for a systematic approach to overcome change barriers. Available energy efficiency metrics were reviewed, and a subset of relevant metrics was suggested to provide data to support investment decision making for both, DC operators and DH operators.

**Publication III**

The main contribution of the publication was a common framework, utilizing best practices, for assessing the energy consumption and $CO_2e$ emissions of the Internet or a sub-segment of it. The economic and social impacts of the Internet were not in the focus of our research. The second contribution was the validation of the framework by utilizing the determined framework to conduct the EIA of online advertising. The third contribution was an approximation of the energy consumption and $CO_2e$ emissions of ad fraud.

The research contributes to the ongoing discussion of methodology in the EIA of Internet-related technologies and services. In addition, a significant consumer of energy was revealed for decision makers and regulators. Even with uncertainties considered, the energy consumption and $CO_2e$ emissions were substantial.

**Publication IV**

The contribution of the publication includes a thorough review of the blockchain technology and its fundamental principles. In addition, the requirements of the online advertising industry for utilizing blockchain as a solution to ad fraud reduction were defined. The third contribution was an analysis of the commercially available blockchain based solutions and platforms with respect to the introduced requirements.

Currently, none of the existing blockchain based solutions for online advertising meet these requirements. The article provides novel recommendations for solution developers on how to proceed in fulfilling the requirements.

**Publication V**

The contribution of the publication is an economic investment assessment of DC waste heat utilization using the NPV model for three different sizes DCs. The data in this model was based on empirical measurements of equivalent rack power consumption, investment prices of equipment and simulated heat market dynamics on a system level. The results together with the marginal-price demand side simulation, investment prices from already conducted projects, and a transparent, open source Monte Carlo simulation tool on input factor sensitivity are novel contributions to the researchers and industry stakeholders.

## 1.4 Structure of the Thesis

The rest of this thesis has been organized into four chapters. In Chapter 2, the theoretical justification for this thesis is presented. This includes the main challenges in ICT energy consumption, possibilities to reduce the environmental impact of ICT, and introduction to two practical case studies on possible solutions to address the ICT energy consumption issue. In Chapter 3, the focus is on DC waste heat utilization, and the related results from Publications I, II, and V. Chapter 4 focuses on online advertising and the related results from the Publications III and IV. Chapter 5 concludes the findings.

# 2. Energy Consumption in ICT

In this chapter, an overview of the main challenges in ICT energy consumption and possibilities to reduce the environmental impact of ICT are presented. Some of the content in this chapter are results from Publication III. Section 2.1 presents the main contributors to ICT energy consumption. Section 2.2 introduces some of the main challenges in ICT energy consumption. Section 2.3 presents some available solutions to reduce the environmental impact of ICT. Finally, Sections 2.4 and 2.5 introduce two ICT energy consumption reduction cases. The results of the cases are presented in Chapter 3 and Chapter 4.

## 2.1 Main Contributors to ICT Energy Consumption

In 2013, the total energy usage of the ICT technology industry was estimated to be 1500 TWh [36]. The total ICT energy usage multiplied by the standard German electricity mix emission factor of 0.5656 kg $CO_2e$/kWh [29] resulted in $CO_2e$ emissions of over 848 million tons. The Internet's share of the global electricity consumption was estimated to be 10% in 2014 [36]: As a reference, the entire global residential space heating in 2014 consumed the same amount [37]. The expectation is that the emissions will grow to 1.3 billion tons of $CO_2e$ in 2020, attributing to 2.3% of the world's $CO_2e$ emissions [15].

Energy consumption is an attribute of two main contributors. First, energy efficiency is the main influencing attribute. Improvements of device-, system-, or DC level energy efficiency reduces the ICT energy consumption and its impact on the environment. An example of an energy efficiency improvement initiative is waste heat utilization in DCs. The second significant attribute is ICT service energy consumption. ICT services that consume less resources and produce less traffic, reduce energy consumption. The correlation is partial because of excess ICT capacity and low energy proportionality of devices. Lower resource consumption decreases the pressure to invest in additional capacity. An example of lower ICT service energy consumption initiative is a reduction of ad fraud traffic. Figure 3 presents the ICT energy consumption and its main contributors.

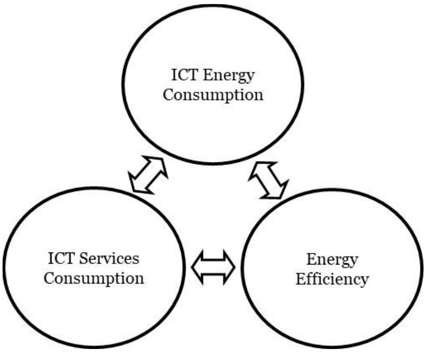


**Figure 3.** ICT energy consumption and its main contributors.

## 2.2 Challenges in ICT Energy Consumption

According to Cisco (2017), data flows of the Internet are expected to grow by 42% annually until 2020 [28]. In addition, the organization for economic co-operation and development (OECD) countries is funding Internet rollouts with billions of dollars to increase Internet use and digitalization [7]. The growth of energy consumption in ICT is increasing despite technological disruptions such as cloud computing, high connection speeds, wireless access, and smartphones and tablets [7]. A Gosselin et al. (2012) study estimated an increasing need for more powerful and energy consuming infrastructure to support the steeply expanding amount of traffic [38]. Cisco and Juniper report overall capacity increments of 54% per annum for core routers, with annual energy efficiency improvement of 18% [32].

There are many stakeholders in the Internet economy. The key stakeholders include more than 300 Tier-2 Internet service providers (ISPs), and tens of Tier-1 ISPs and Internet exchange points (IXPs) providing locations where multiple networks exchange traffic and routes [39].

The continuous increase of digital services such as streaming video, web browsing and data exchange over time has attracted attention to the environmental impact of the Internet. The direct environmental impact of digital services results from the energy consumption of devices involved in delivering the service, and from the resources consumed by manufacturing and disposing of the devices [32]. Clouds and DCs are changing the traditional way of assessing the environmental impact of the Internet [4].

In Publication III, the total use-phase energy consumption of ICT was assessed (manufacturing and disposal phases of the devices were excluded) with the system boundary presented in Figure 4.

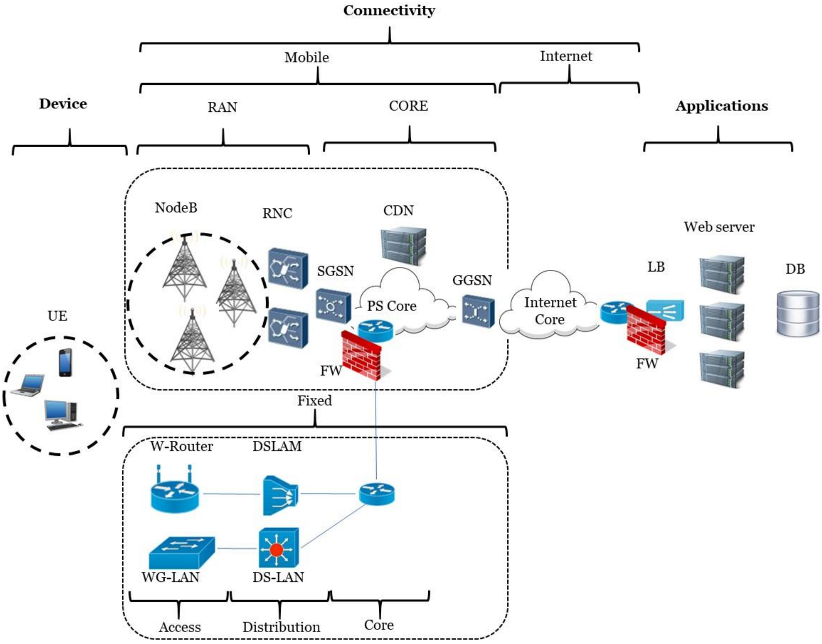


**Figure 4.** The system boundary of ICT energy consumption assessment [Publication III].

The use-phase energy consumption of the ICT infrastructure (2016) was 1058 TWh (including uncertainty the results were from 839 to 1278 TWh). The distribution of the results is presented in Figure 5.

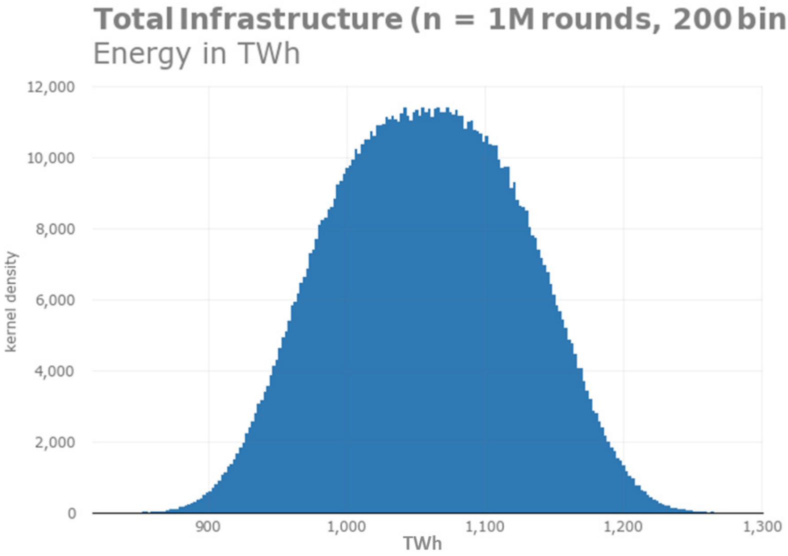


**Figure 5.** ICT infrastructure total energy consumption distribution [Publication III].

## 2.3 Reducing ICT Environmental Impact

There are several known ways to reduce the environmental impact of ICT. Figure 6 presents a non-conclusive mind map covering some of the ideas already implemented or being researched [40]. In the following paragraphs, some of these concepts (marked with a blue flag in Figure 6) aiming to reduce the environmental impact of ICT are briefly introduced.

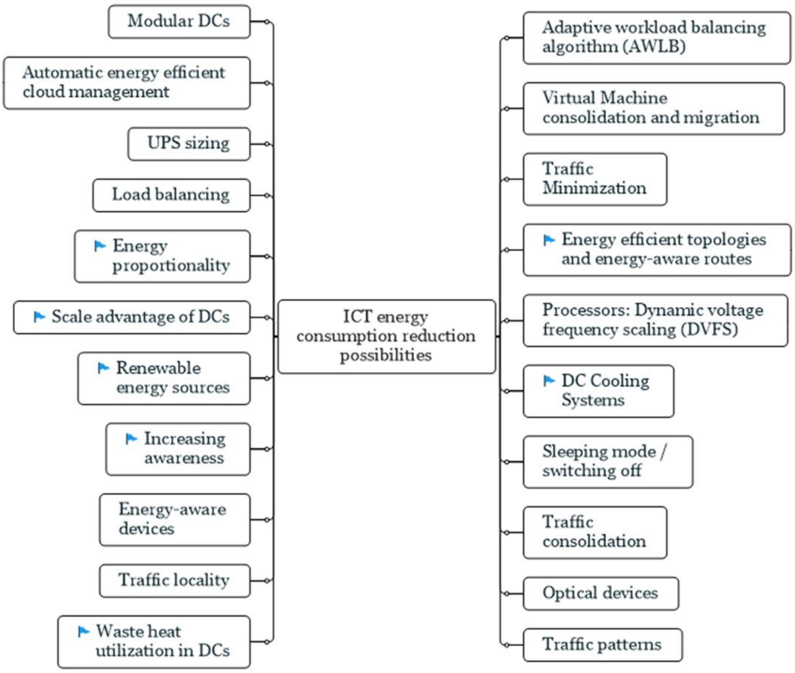


**Figure 6.** Mindmap of potential solutions to reduce the environmental impact of ICT.

### 2.3.1 Increasing Awareness

DC operators are not intuitively willing to change operational production environments. According to the Fujitsu ICT Sustainability report (2011), ICT sustainability is not a high priority for most ICT departments [41]. The same study identifies, thet the single most important reason ICT managers and leaders do not prioritize sustainability, is the lack of visibility regarding actual energy consumption. Only 15% of ICT managers include the cost of ICT energy consumption in their ICT budgets. The Fujitsu report has indicated that the lowest awareness index score comes from the energy efficiency metrics [41].

### 2.3.2 Renewable Energy Sources in DCs

To have a green image, DC operators have different strategies for using renewable electricity. A DC operator can produce their own electricity on-site or off-site. In addition, or as an alternative, they can purchase electricity certified as green energy (e.g., green certificates, a guarantee of origin, and power purchase agreements).

DCs use on-site and off-site renewable energy (transported through a grid) from, e.g., wind turbines, solar panels or wave energy in order to become less dependent on black energy from the grid [42].

There are four key challenges and requirements for renewable energy [43]. Firstly, global users require 24/7 cloud services; therefore intermittent renewable energy represents a problem for DCs, which are consistent users of power. To mitigate the varying nature of renewable energy, DCs can store renewable energy in batteries or on the grid. Secondly, cloud capacity demand is dynamic, which requires dynamic power provisioning. Thus, the power supply should be elastic. Dedicated renewable energy cannot be scheduled on demand. Thirdly, high-reliability services incur the problem of how to construct a reliable power supply in the presence of uncertain dedicated renewable energy. Fourthly, automatic management requires the power supply system to choose and supply power automatically among multiple power sources.

Experiments with real power demand and renewable energy sources showed that there are several advantages to using renewables. Firstly, renewable energy can lower both $CO_2$ emissions and energy costs for DCs. Secondly, on-site renewables can reduce costs by reducing peak power drawn from the grid. Thirdly, the most cost-efficient alternatives for $CO_2$ reduction vary with different carbon footprint targets. For a reduction target up to 30% the best option is to use on-site renewables. If the reduction target is higher than 30%, offsite renewables are required [43].

### 2.3.3 Scale Advantage of Large DCs

Large-scale DC practices provide a few key benefits. Firstly, server, networking, and administration costs for a cloud provider can be five to seven times lower than those for an average private provider. Secondly, the actual cost of power consumed by the servers plus the cost of cooling the servers is 34% of the total cost of ownership (TCO) [44] of a DC, whereas amortized server costs during a 10-year lifetime of a DC form 54% of the TCO [45]. Cloud service providers typically own geographically distributed DCs. In theory, this could mean that they can distribute workloads among geo-dispersed DCs to utilize the location diversity of different types of available renewable energies [43]. Cloud DCs support a wide range of IT workloads. One type of workload includes delay-sensitive non-flexible applications, such as web browsing. Another type of workload includes delay tolerant, flexible applications, such as scientific computational jobs. Workload flexibility could overcome the challenges of integrating intermitted renewable energy. This could be achieved by delaying flexible workloads to periods when renewable sources are abundant without exceeding their execution deadlines [43].

### 2.3.4 Energy Proportional DCs

An energy proportional DC means that a global power manager controls the operational status of servers to supply sufficient computing capacity to handle the current demand, cutting energy usage by hibernating redundant servers. A reduction in computing capacity can impact service quality [46].

There are two ways to reduce the cost of energy consumed in DCs. The first way is to use efficient placement algorithms to reduce energy consumption. These algorithms could operate inside a single DC (for example, deriving more efficient routing algorithms to reduce the power consumption in DC network switches) or across DCs. Example of such an algorithm is DC energy efficient network-aware scheduling (DENS) [47]. DENS methodology minimizes the total energy consumption of a DC by selecting best-fit computing resources for the execution of a job, based on the load level of the servers and communication potential of the DC components. The DENS methodology is meant for a three-tier DC architecture. The three tiers are namely the core network, the aggregation network, and the access network [47].

The second way is to move the applications to DCs located in areas where the cost of energy is relatively low. Energy-efficient DC algorithms mainly fall into two classes. VMPlanner is a combination of virtual machine (VM) placement and network routing algorithms. VM placement algorithms attempt to consolidate VMs onto the fewest number of servers. Efficient network routing algorithms attempt to do energy efficient routing by consolidating the network traffic onto the smallest number of links [47].

### 2.3.5 Waste Heat Utilization in DCs

In 2010, energy efficiency was not a dominant design criterion for DCs [48]. Nevertheless, energy has become a critical factor in DC profitability and competitiveness [10], [49]. In addition, the increase in energy consumption will become a critical concern also to DC customers [50]. Recently, there has been active competition between countries to attract new DC investments. For example, Sweden offers the lowest total cost of electricity in the EU resulting from a 2017 government decision to cut energy taxes for DCs. Sweden also states that it is the EU leader in sustainability, and it has the highest share of renewable energy sources coupled with a 98 percent carbon-free energy footprint [51].

There are two strategies to improve DC sustainability: improving energy efficiency and increasing the use of renewable energy [11]. Current energy efficiency activities in DCs include increasing power-feeding technology efficiency, aisle capping, reusing waste heat and fuel cell technology utilization [52].

The issue of energy efficiency in DCs is a rising concern, as more and more data is saved, processed and transferred to offer a multitude of digital services. It has been suggested that centralized DCs are more efficient energy-wise than individual and distributed information technology (IT) [53]. In addition to the direct electricity consumed by the ICT hardware and necessary infrastructure, DCs require vast amounts of cooling energy, typically produced with air conditioning units. It has been suggested that excess waste heat from thermal power plants could satisfy the total heat demand for buildings in Europe [54].

### 2.3.6 DC Cooling Systems

DC cooling is one of the crucial areas where new energy efficient solutions are being presented. DC cooling consumes a significant amount of energy, and it is a popular research topic. Energy efficient solutions need to be decided when investing in a new DC, but also when modernization is taking place. Especially dynamic systems with dynamic control possibilities are considered significant [55].

There are several solutions for DC cooling. The main cooling methods are free cooling, mechanical refrigeration, or a combination of both (the most common method). Refrigeration solutions consume substantial amounts of energy and are therefore less profitable compared to free cooling solutions. In free cooling, the cooling capacity of ambient air, seawater, or ground is used to chill water that cools the DC. Free cooling is not always possible, as the ambient temperature may be too high. Mechanical refrigeration can be used to produce the additional cooling energy required, for example when the outdoor temperature is over 15 °C. Free cooling is popular in Nordic DCs because of favorable outside temperatures for most of the year [56].

Air cooling has been the most common method for cooling the DCs in the past. Air cooling has its limitations and cannot be used as effectively in more modern DCs [56]. Emerging technologies for cooling DCs also include solutions such as liquid cooling and district cooling. Liquid cooling can be conducted by at least two different methods: 1) coolant liquid can be brought to the racks by pipes rather than providing the coolant to chill the air, and 2) the on-chip cooling solution brings the coolant to the processors. The benefits of liquid cooling are notable, especially for waste heat utilization. The coolant liquid can be of a higher temperature, thus making it possible to capture better quality waste heat. With on-chip cooling, the waste heat is also easy to capture, as the heat can be captured directly from the local chip [56].

District cooling is a potential cooling solution for DCs. District cooling can utilize the same distribution network as DH. The cooling energy is mainly produced by the DH network operator. Cooling energy can be produced, for example, by heat pumps, by absorption refrigerators, or even by free cooling. The supply temperature in district cooling is typically between 7 and 10 °C [57]. For a DC operator, district cooling is also a good option because it requires less space as in the case where cooling energy is produced in a DC.

### 2.3.7 Energy Efficient Topologies and Energy-Aware Routes

Energy efficiency can be sought in the telecommunication networks. There are many energy efficient architectures and routing algorithms [58]. Energy-proportionality can be achieved on device level or overlay level. The main idea is to turn off excess devices or links and bring them back online when the capacity is needed. Energy efficient solutions in virtualization are a collection of live migration tools and scheduling heuristics. Both can become a competitive advantage for a cloud service provider. Virtualization is one of the leading technologies used in modern DCs, and the idea is to increase the utilization rate of the equipment. Virtualization is also used in networking as a norm [58].

### 2.3.8 Processors

Dynamic voltage frequency scaling (DVFS) technology adjusts the central processing unit (CPU) frequency and voltage usage [59]. The DVFS technique lowers the frequency and voltage when the processor is lightly loaded, and utilizes maximum frequency and voltage when the processor is heavily loaded [60]. Employing DVFS techniques and using commodity server designs lead to energy efficiency at the cost of performance [60], [61]. Even though the individual DVFS net reduction of CPU energy consumption is low, the number of CPUs is enormous, and therefore the significance is high [59].

## 2.4 Case: Energy Efficiency – DC Waste Heat Utilization

A Stratego Project (2017) study estimated the total amount of EU waste heat to be 3140 TWh [62] (56 TWh is DC related [63]). Reusing DC Waste heat reduces $CO_2$ emissions and other harmful gases [64].

DCs are the main components of digitalization and cloud computing [11]. The number of DCs has grown due to the increasing demand for data processing. Furthermore, the size of DCs has increased, and there is an ongoing trend in the consolidation of DCs into larger entities [65], [66]. The annual increase in DC energy consumption is estimated to reach 15–20% [44], [64], [67]. This change in the DC industry favors the utilization of waste heat, as the heat sources are more significant and can offer a secured supply of heat.

Many studies concerning facility energy efficiency in DCs have been conducted recently. Most of the facility energy efficiency studies are related to efficient cooling systems, electricity consumption and integrating renewable electricity with DCs. Instead, reusing waste heat from DCs is less studied, but in recent years research has become more topical and some case studies have been conducted.

According to Paolo Bertoldi (2014), making DCs more energy efficient requires a concerted effort to optimize power distribution, cooling infrastructure, IT equipment, and IT output [68]. Massoud Pedram et al. (2012) have suggested that the economics of operating a DC is comprised of four main factors that contribute to the TCO of a DC [45]. The factors are resiliency, downtime, financial considerations, and vertical scalability.

Energy-efficiency targets have increased for the modern new DC sites. According to a large Finnish DC operator, Telia Company (2015), the operation of their new DC generates 200 GWh of heat annually [69]. Hence, the possibilities to provide the waste heat to a DH grid has been utilized to reach the energy-efficiency targets.

A heat reuse solution allows DCs to sell the waste heat to a third party, such as a DH operator. Two alternative business models have emerged: 1) DC operator invests and operates waste heat equipment, and 2) DH operator operates the equipment. The choice of a business model also affects the pricing of waste heat energy.

This case investigates the viability of DC waste heat utilization as an energy efficiency improvement solution and is based on results and findings from Publications I, II, and IV.

## 2.5 Case: ICT Service Use - Online Advertising

In the US, online advertising revenue has risen from $26B in 2010 to $42.8B in 2013, and up to $73B in 2016 ([70], [71]). According to Chen et al. (2016), global mobile advertising revenue grew by 92% from $10B in 2012 to $19.3B in 2013 and was expected to rise by 100% per year until 2016 [34]. Operators continue to upgrade their infrastructure to keep up with this pace and to support extra overhead [34].

Many websites rely on online advertising as a source of revenue, and a typical web page has many ads on it. Online ads use rich graphics, animation, and video, which consume more processing and energy than the rest of the content. Hypertext markup language 5 (HTML5) supported rich media ads are displayed directly on end-user devices. An ad occupies a small portion of the user's display but involves CPU intensive computing processes. The ad format is driving the CPU use and energy consumption. The increasing number of ads is counterproductive to the environment [72].

In addition to online ads, the ad industry utilizes trackers, which are small pieces of code residing on websites [73]. Trackers are used to tracking users' browsing behavior and to deliver online ads based on this data [73], [74]. A study conducted at Princeton University (2016), consisting of an analysis of 1 million websites, found massive amounts of hidden trackers embedded in websites [74]. The study found that over 81 000 individual third parties present in at least two websites. Third parties responsible for trackers engage in a practice referred to as cookie-syncing. Cookie-syncing is a technique where multiple tracking tags are included in a single container. When the end-user loads the container, connections are established to the DCs associated with the tags inside the container [74].

According to Solarwinds 2018 study, the average load time for the top 50 websites was 9.46 seconds with trackers and 2.69 seconds without trackers. This additional load time is energy consuming. The same study found 298 individual trackers in the top 50 websites, out of which 225 (75%) were associated with online ads on the website. On average, news sites have 41 different trackers. In addition, 42% of the sampled sites loaded with 30 to 49 trackers, highest having 85 trackers [73]. The News category of sites has the highest number of trackers [74]. Each tracker increases the download time and the total amount of downloaded data on a website.

The online advertising ecosystem has many stakeholders between the advertiser and the web page requesting an ad. Typically, a publisher leases ad spaces to an ad network. When a user connects to a web page with ad spaces, an ad request is generated. The request is passed to the ad network, which in turn can forward it to other ad networks or the supply side platform (SSP), passing through many intermediaries before arriving at the Ad Exchange. The process until this point is called the supply side.

The Ad Exchange proceeds to a bidding process. This part of the process is called the demand side. The standard for a bidding process is the open real-time bidding (RTB) protocol. An Ad Exchange generates a bid request according to the openRTB standard [75]. The bid request is forwarded to the demand side platforms (DSPs), which are registered in the Ad Exchange in question. The DSPs configure programmatic advertising campaigns. When a bid request is received, the DSP verifies a match to the configuration parameters of any of its ongoing campaigns. If there is a match, the DSP generates a bid response with the price the advertiser is willing to pay to display its ad on the web page. The latency of bid responses to a given bid request received by the Ad Exchange must be less than 100 ms [76]. The Ad Exchange runs an automated auction and informs the selected winning bid to DSPs. The Ad Exchange coordinates the delivery of a URL of the ad, which is downloaded by the web browser. A delivered ad is referred to as an ad impression. This whole process is presented in Figure 7.

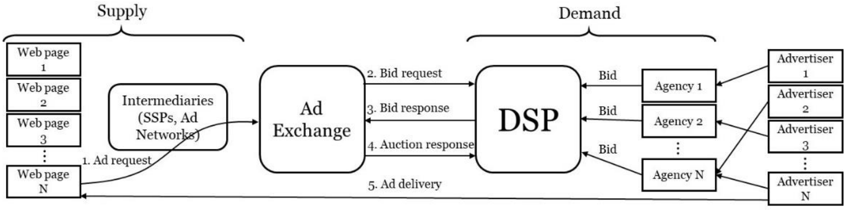


**Figure 7.** Online advertising ecosystem [Publication V].

Ad fraud is common in the online advertising ecosystem. Examples of ad fraud include advertisers paying for advertising space not seen by consumers [77], traffic that is generated by bots, and other means. All programmatic impressions can be exposed to ad fraud [78]. The amounts of ad fraud vary between 15-30% [79], [80]. The situation is similar across video and banners. In 2014, the association of national advertisers (ANA) reported that 23% of video views are fraudulent [79]. Ad fraud is approximated to grow to $50 billion by 2025 [78]. Transparency issues aggravate ad fraud. Almost 30% of the top 5000 websites use privacy solutions that prevent the possibility to connect the website to any individual or company for media buyers [78]. Other transparency challenges include a lack of pricing information, black box bidder strategies, and masked inventories [81].

From an energy consumption perspective, a typical scenario for online advertising is where an end-user device requests a webpage, and the webpage makes requests to dozens of DCs, some of which keep the connection open with the end-user throughout their visit to the page. The connection can be kept open even when the user is idling, resulting in always-on connectivity. As long as the user is not moving to the next page, or closing the browser window, the connection remains in the high-power state. This case investigates the environmental impact of online advertising on ICT energy consumption and assesses if blockchain can be a potential solution to remove some of this unwanted ad fraud traffic from the network and therefore reduce the energy consumption of ICT. This case is based on results and findings from Publications III and IV.

# 3. Data Center Waste Heat Utilization

This chapter investigates the validity of the waste heat utilization solution in a DC environment from different perspectives. The results and findings in this chapter are from Publications I, II, and V. Section 3.1 provides a literature review on the key waste heat reuse related topics found together with co-author M. Wahlroos. Section 3.2 presents the results from Publication I and analyses DC as a source of waste heat and how it impacts DH production. Section 3.3 presents the results from Publication V and assesses the economic viability of waste heat utilization investments. Section 3.4 presents some of the most interesting waste heat utilization projects in the Nordics from Publication II. Section 3.5 introduces critical success factors (CFSs) in waste heat utilization projects from Publication II.

## 3.1 Literature Review

The location of a DC effects energy efficiency. Depoorter et al. (2015) studied the electricity generation portfolio, on-site generation and cost of electricity in different locations [82]. The study showed that depending on the location; direct free air cooling could save from 5.4% to 7.9% of the electricity consumed. Electricity is cheaper in Sweden than for example in Germany, and a smartly located DC could save up to 42.5% in energy costs. Due to the high proportion of hydropower and nuclear power in Sweden, a DC in Stockholm would produce over 30 times less $CO_2$ emissions than a DC in London [82].

Different applications of waste heat utilization have been studied. Lu et al. (2011) investigated energy efficiency and the potential for waste heat capture in a DC in Finland [83]. The study demonstrated that 97% of the power consumption could be captured as waste heat. The conclusion was that waste heat from a 1 MW DC, operating at half of its nominal load, could provide heat for over 30 000 m2 non-domestic building annually. Marcinichen et al. (2012) demonstrated that low-quality waste heat from a DC could preheat feed water of a power plant [56]. Utilization of waste heat would lead to power plant fuel savings and increase the efficiency by up to 2.2%. Ebrahimi et al. (2015) studied waste heat utilization by using absorption cooling machines [64]. The study showed that the payback time for a retrofitted absorption system could be 4-5 months in a 10 MW DC. Sorvari (2015) studied waste heat utilization in heating a spa and rental cottages in Northern Finland [84]. The results showed that the DC waste heat would provide heating for cottages over 60 000 m2.

Cost saving potential has also been studied. Kupiainen (2014) compared two cooling options for a DC in Jyväskylä, Finland. The study suggests that a combination of free cooling with heat pumps resulted in 0.28 M€ lifetime savings compared to free cooling and refrigeration machine in 20 years [85]. Stenberg (2015) simulated a 3 MW DC in Helsinki, Finland [86]. The study showed that waste heat reuse could result in lifetime savings of millions of euros. The most cost-efficient system would be a heat pump priming the waste heat to 75 °C and selling heat to either supply or return side of the DH network depending on the outside temperature [86].

Waste heat utilization in DH has been studied as well. Davies et al. (2016) investigated the possibilities of DH in London and the potential for waste heat utilization [87]. The possible savings for DH were calculated assuming the natural gas-based heat production would be replaced by waste heat. The study showed that using liquid cooling in DCs would generate the most savings in energy as well as in carbon savings. The annual cost savings, in this case, could be over £875 000 in the case of a 3.5 MW DC with UK renewable heat incentive [87].

Based on the literature review, both technical solutions for waste heat utilization and case studies have been conducted, but commercialization of waste heat has hardly been done, even though the conducted studies show that waste heat reuse results in significant savings in energy costs with considerably low pay-back periods.

In the following sections, the key concepts for DC waste heat utilization are presented.

### 3.1.1 Data Center and Waste Heat

Thermal management is one of the critical activities in DC. An energy efficient DC has inlet air to all systems maintained at a specified temperature. Exhaust hot air is prevented from mixing with incoming cold air and driven back to air conditioning units. Air conditioning resources are also set to deliver proper mass flow for given geometric distribution of heat loads. An energy efficient DC operates through a pervasive sensing layer - a network of hundreds of temperature sensors at the inlet and outlet of the servers in the racks. A DC management system, based on high-level thermo-fluids policies enables automated dynamic provisioning of air conditioning resources, distribution of computing workloads for power management, and maintains a DC in a provisioned state entirely in balance with heat loads [88].

An existing DC provider with out-of-date equipment and poor energy efficiency has six strategic alternatives; 1) modernize the existing DC, 2) invest in a new DC, 3) migrate workloads to a large co-location DC operator, 4) migrate workloads to a public cloud provider, 5) utilize other means to improve energy efficiency, like implementing energy management system (EMS) to optimize workloads of a DC with migrations, consolidations and shutting down idle nodes, or 6) do nothing. Modernization of the existing DC is a valid option if there are obstacles to transforming workloads into a large co-location DC operator or public cloud. Possible obstacles include; 1) security, 2) pay-as-you-go pricing models, 3) service level agreements (SLA), and 4) natural lock-in. In addition, migrating workloads to a large co-location DC operator or a public cloud should have a significantly lower cost level than current DCs cost. A better strategy would be to identify decision criteria for whether a given application is hosted internally or moved to a cloud environment [89].

The two most essential issues in DC waste heat utilization are heat demand and profitability. There must be a particular demand for heat in the near vicinity. Heat cannot be distributed over long distances efficiently. Marginal variable costs of waste heat are mostly very low. Marginal variable costs can become significant if a heat pump is used and electricity is expensive. Therefore, sales of waste heat or replacing the costs of required heat production have to cover the investment costs of the equipment, as well as the costs of connecting to the heat distribution.

### 3.1.2 District Heating and Waste Heat

DH is founded on centralized and efficient heat production. DH is a mature technology used to deliver energy to urban areas. In the last three decades in the EU, the annual supply of DH has been approximately 700 TWh [90]. Investing in a new DH infrastructure in a pre-built environment could be expensive, but DH infrastructure can also be built on a smaller scale for new housing areas [90]. The DH supply temperatures in Finland are typically around 75-120 °C [91]. As the houses become better insulated, DH networks are seeking ways to lower temperatures, which would enable lower quality heat to be fed into the DH network.

To comply with the EU regulations, for example, Finland is aiming at near zero energy buildings (nZEB) in the new building stock by the year 2020. The deficient energy demand of the new buildings is particularly suitable for fourth-generation DH systems providing low-temperature heat supply [91]. Therefore, there may be even more potential for utilizing the waste heat from DCs in the future. If the supply temperature of the DH network can be decreased to as low as 50 °C, lower quality heat would be easier to feed into the system. Typically, waste heat from DCs is low quality (<85 °C), and thus it cannot be utilized in current networks to its full extent. DH networks can absorb large amounts of heat, which make DC waste heat utilization possible for larger DCs. DCs should locate near a DH network to ensure efficient transfer of heat. Retrofitting an old DC in a rural area is usually not a feasible candidate for waste heat utilization in DH networks. Waste heat utilization as a potential business opportunity should be one of the DC investment decision attributes.

The supply temperature is selected to suit the needs of the most demanding customer, resulting in excessive temperatures for ordinary customers [92]. Buying waste heat from external sources may have significant cost benefits for DH network operators by replacing more expensive peak load production. Also, fossil fuels are typically used for peak load production. There is a possibility that waste heat utilization can remove the need for investing in new heat production capacity, but only if the source of waste heat is reliable.

### 3.1.3 Requirements for DC Waste Heat Utilization in DH

The main deciding factors for waste heat reuse are the location of DC, the price-, and the quality of waste heat. The quality of the heat refers to temperature and availability of the waste heat. In the summer, mainly on heating domestic hot water (DHW) is required. DH demand is highest during the winter. It is important to analyze whether the supply and the demand for heat meet.

DCs may be operating on shorter periods compared to new heat production plant investments. DCs are typically committed to contracts and clients on the maximum 5-year time period. Heat production unit investments typically have technical lifetimes of two to four decades. Varying time horizons may lead to challenges in contracts as DCs may be reluctant to commit themselves to long binding contracts on supplying waste heat.

Waste heat from DCs is typically low temperature, but the temperature can be increased with heat pumps, thus requiring additional electricity. Also, heat pumps could produce cooling energy for the server room. However, heat pumps are usually not used as the only source for cooling energy.

The best locations for capturing waste heat have been investigated in [64] and [87]. The temperature of waste heat depends on cooling technology and the location where it is captured. In air-cooled solutions, waste heat can generally be captured between 25 °C and 35 °C. In liquid cooling solutions, waste heat can be captured closer to CPUs, where temperatures of captured waste heat can be between 50-60 °C.

Waste heat is typically recovered from hot aisles in the ventilation system. Figure 8 explains the configuration of a waste heat recovery system for a remote air-cooled DC, where waste heat is utilized in a DH network. The chilled water is supplied to the computer room air conditioner (CRAC) or computer room air handler (CRAH). CRACs produce the cool air that is pushed to the cold aisle via a perforated and raised floor. Waste heat is recovered from the hot aisles to the ventilation system. The collected waste heat can go through different stages, e.g. an evaporator and a condenser, and subsequently a heat pump to be able to be used in the reuse application (e.g. a DH network). To make the heat transfer, heat pumps are connected to the supply and the return side of the DH network. Cooled waste heat can then be directed back to the cooling system of the DC. Davies et al. studied the possibilities of DH networks in London and the potential for waste heat utilization [87]. The study showed that using liquid cooling can provide the best quality waste heat from DCs and would, therefore, generate the most savings in energy as well as in $CO_2$e emissions. More details on DC waste heat connection to DH can be found in [87], [93].

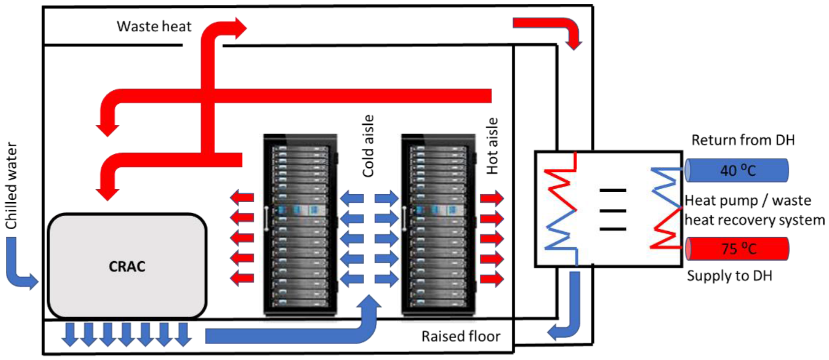


**Figure 8.** Configuration for a waste heat recovery system for a remote air-cooled DC, which utilizes waste heat in DH [Publication I].

The coefficient of performance (COP) of the heat pumps in DCs typically ranges between 3.0-6.3 [87] and the COP decreases when the desired temperature is increased. COP is a ratio of useful heating or cooling provided compared to the consumed energy. Higher COP values indicate lower operating costs and higher gains. Å Stenberg (2015) has studied COP and power usage effectiveness (PUE) relation in the temperatures of 60°C, 75°C, and 90°C. The corresponding COP/PUE values were 4.9/1.29, 3.5/1.36, 2.2/1.68. Without waste heat utilization the PUE value was 1.2 [86]. Therefore, with lower heat pump COP values the energy consumption of DC increases, therefore PUE increases.

### 3.1.4 Energy Efficiency and Waste Heat Reuse Metrics

A challenge in the DC industry is the lack of a credible, appropriate, and industry-acceptable standard method to allow available energy efficiency metrics to be applicable for power usage calculation [94]. By using existing, commonly known metrics, it is not possible to distinguish energy efficiency of a DC communication system from the energy efficiency of computing servers, as both are considered under a common umbrella of IT equipment [95].

The first step in energy efficiency improvement is to evaluate the energy consumption and DC environment adequately. The step is achieved by measuring holistic performance with a set of energy efficiency metrics [55]. Energy efficiency improvement of DCs is associated with challenges due to limited monitoring, efficiency measurement and evaluation, and even cooling system capabilities. Measuring the energy efficiency and performance of a DC by using holistic metrics allows tracking improvements and changes, estimating the impact of the changes, and comparisons to other technologies and average industry performance [55].

The Green Grid has specified four characteristics of efficient DC metrics: 1) intuitive metric name, 2) scalability to techno-economical changes, 3) scientific accuracy, and 4) the granularity to provide data-driven decisions [94]. A vast number of energy efficiency metrics that measure energy consumption exist, aimed at reducing the total consumption of electricity in DCs. The most widely adopted energy efficiency benchmark metric is PUE. PUE is defined as the ratio of the total power used by a building site, divided by the amount of power used by the IT equipment [55].

Song et al. (2015) measured power consumption in 10 DCs, and the division was: IT 45%, cooling from 30% to 55%, power distribution 13% and lighting 3% [66]. Several recent studies suggest that on average 40% of the power is consumed by cooling [10], [44], [50]. Based on these results, the PUE value is within the range from 1.72 to 2.22.

PUE is overly simplified and does not provide the technical base for proper engineering analysis [94]. Also, PUE does not address the benefit of waste heat capturing and reuse. According to S. Zimmermann et al. (2012), energy reuse effectiveness (ERE) has been designed to measure the benefits achieved by introducing waste heat reuse from a DC [96]. The Green Grid has defined ERE to be used similarly as PUE including the reuse of energy effect from a DC. ERE is defined as the total annual energy use minus the total annual energy reused external to the DC all divided by the annual energy use of the IT [97]. Only when energy is reused outside the DC will it affect ERE. Any reused energy interior to the DC will be realized in a lower PUE and is not credited in the ERE calculation. energy reuse factor (ERF) was created to assist in an understanding of ERE. ERF is defined as a ratio of the reused energy from the DC and the total energy used by DC. ERF can be used to calculate ERE from the site PUE [97]. The ERE and ERF equations with the theoretical limits are:

$$ERE = \frac{Total\ Energy - Reuse\ Energy}{IT\ Energy} = \frac{Cooling + PowerDistribution + Misc + IT - Reuse}{IT} ;$$

$$0 \leq ERE \leq \infty \qquad (1)$$

$$ERF = \frac{Reuse\ Energy}{Total\ Energy} ; \qquad 0 \leq ERF \leq 1.0 \qquad (2)$$

$$ERE = (1 - ERF) \times PUE \qquad (3)$$

Adaptation of ERE in the industry is based on implemented waste heat recovery solutions. As PUE is still the de facto benchmark metric, the implication is that the majority of DCs do not reuse waste heat.

Regulation should be set on measurement methods to calculate the energy efficiency and to achieve the desired objectives. Measurement conditions such as SLA should be followed while measuring values.

### 3.1.5 Investment Assessment Methods and Tools

The capital expenditure (CAPEX) assessment decision criteria depend on the objective of the opportunity. Some CAPEX opportunities are accepted without quantitative criteria, such as investments in maintenance, pollution reduction, safety improvements, or complying with the legislation. Generally, CAPEX is subject to quantitative assessment, with the level of detail depending on the size and risk of the project and the managers' appetite for risk [98].

Financial analysis can be performed utilizing different methods and tools. Researchers have categorized the investment assessment methods into five types; NPV methods, rate of return methods, ratio methods, payback methods, and accounting methods [99]. The best practices for investment efficiency evaluation include NPV, internal rate of return (IRR), discounted payback period (PB) [98], [100], return on investment (ROI) [49], [101], TCO, and real option analysis (ROA) [102].

NPV is the most frequently used method for assessing the economic effects of investment. NPV leads to better investment decisions because it recognizes a time value of money, depends solely on the forecasted cash flows, and all values can be added as they are present values [103]. Decisions based on average cost can be 10% worse compared to NPV based decisions [99]. Finance theory endorses investment if NPV is positive with the chosen rate of return. Positive NPV can be reached when the present value of cash inflows exceeds cash outflows [103], [104]. The NPV model requires the following variables to be forecasted: 1) investments, 2) operating revenues, 3) operating costs, 4) economic life of the project, 5) inflation rate and 6) interest rate [49], [99], [103]. NPV is based on proven principles but contains many assumptions resulting in an inherent uncertainty. Actualized results may deviate from expected long-term values [104].

Calculating NPV has four critical steps: 1) estimation of future operating free cash flows (OFCF), 2) estimation of a rate of return factor r, and discounting the future cash flows into the present value (PV), 3) computing the NPV value, and 4) evaluating the results [103]. The IRR was also calculated (Brealey et al., 2012). It was used to estimate the profitability of investments. IRR is an r that makes NPV of an investment opportunity equal to zero [49], [105]. A project should be approved if the IRR of the project is higher than the selected rate of return factor [98]. All investment opportunities with IRR below the risk-free rate are unprofitable under present market conditions [102].

ROI is an index representing the ratio between earnings and the amount invested [49]. The higher the ROI%, the better the investment. Note that ROI does not consider the time value of money as NPV does. PB is the inverse of ROI [49]. It is the period the project is expected to take to earn revenue equal to the capital cost within the discount period. It is calculated as the ratio between total CAPEX and the cash flow, taking into account the rate of return factor. The PB method does not take cash flows into account after the cut-off period [105]. The PB period is often used together with the NPV analysis. A PB period of around three years is considered a reasonable level [98].

## 3.2 DC as a Source of Waste Heat and Impact to DH Production

In Publication I, waste heat generation was simulated based on data measured from actual DC production systems. The DC measured represents a typical private cloud service provider profile with multiple different sized customers utilizing shared infrastructure and services. No direct free cooling is used. The monthly average PUE value of the measured DC was 1.5.

Load-balanced server backup traffic from the core network router link was measured. Backup traffic was sequential as expected and peaked between 9 PM to 7 AM. The service traffic in/out of the DC was measured from the Internet breakout routers' ports. The traffic was highest from 7 AM – 10 PM. Weekends showed lower service traffic. It can be concluded that in a service provider DC the combined service traffic and backup traffic form a uniform network traffic profile, which is almost uniformly spread across each hour of the day.

Figure 9 illustrates the power usages of four VMware Elastic Sky X (ESX) servers from the measured DC. The role of these servers was to host the virtual servers of customers. The power consumption was stable. Figure 10 illustrates power consumption volatility on each of the servers during a 24-hour period. Figure 11 illustrates the volatility on each of the server central processing unit (CPU) utilization percentage. The minimum and maximum were in the 20% range throughout the measurement period. The conclusion from Figure 9 together with Figure 10 and Figure 11 data is that power consumption and payload processing were almost uniformly spread across each hour of the day.

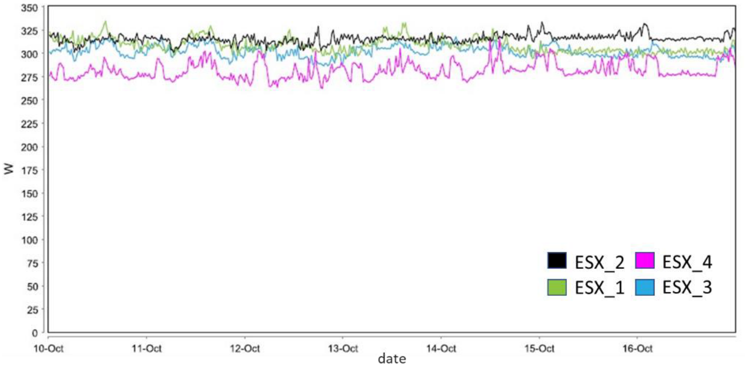


**Figure 9.** Four ESX power consumptions as a function of time [Publication I].

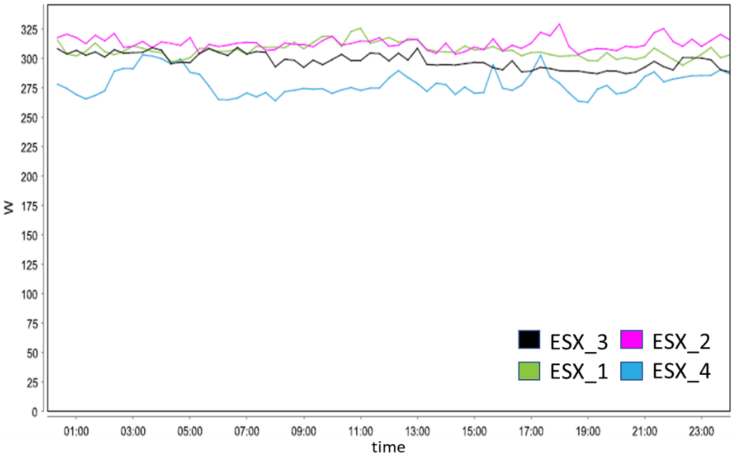


**Figure 10.** Four ESX power consumptions during 24 hours [Publication I].

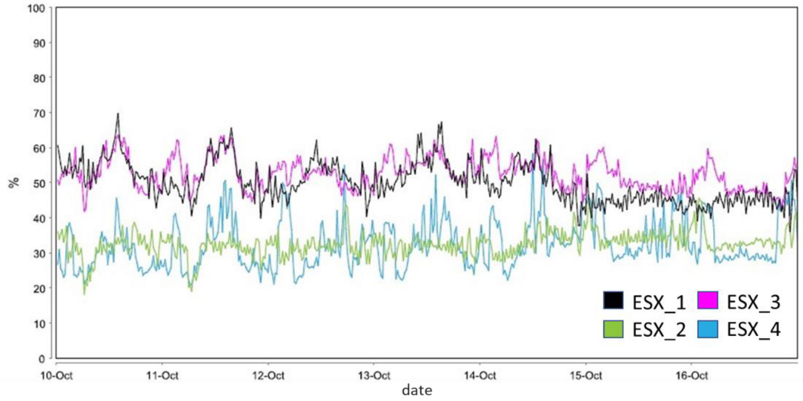


**Figure 11.** Four ESX server CPU usages (%) [Publication I].

The combined results of Publication I imply that the service provider DC operates close to a uniformly distributed load profile and power consumption every hour of the day. Altogether, this suggests that DC as a whole is a stable source of waste heat each hour of the day.

Based on the measures, power consumption is not directly proportional to workload fluctuation. Therefore, it was possible to use Figure 12 as the basis for the simulation of waste heat production of a DC. Figure 12 provides evidence that IT electricity consumption correlates strongly with heating, ventilation, and air conditioning (HVAC) electricity consumption.

According to the measured service provider, part of the fluctuation in electricity consumption could result from the renewal of equipment and changes in the customer base. Statistical analysis in Figure 13 and Figure 14 reveal that the fluctuation in the overall electricity consumption is positively correlated with average monthly outside air temperature. The positive correlation is higher when the average monthly outside air temperature is above 10 °C. Below that point, electricity consumption varies more as a function of facility and IT-equipment electricity consumption and can be considered to be almost constant. In all situations, the heat resulting from IT-electricity consumption can be reused.

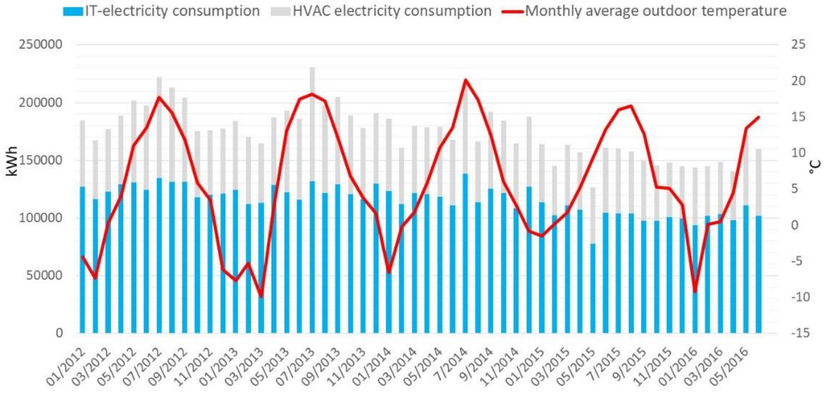


**Figure 12.** Monthly electricity consumption of the production DC and average monthly outside temperatures in Espoo [Publication I].

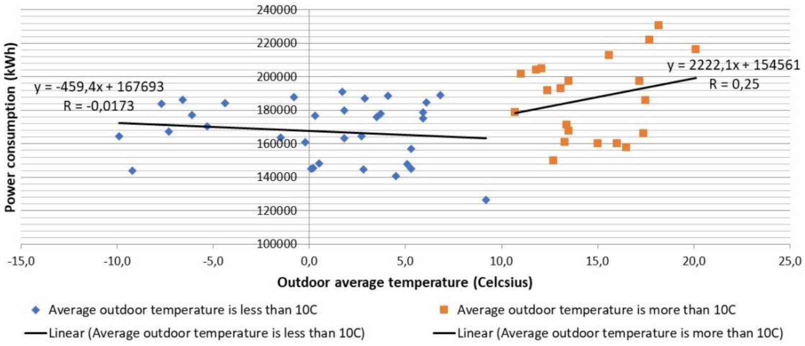


**Figure 13.** Scatter chart on power consumption and average outdoor temperature [Publication I].

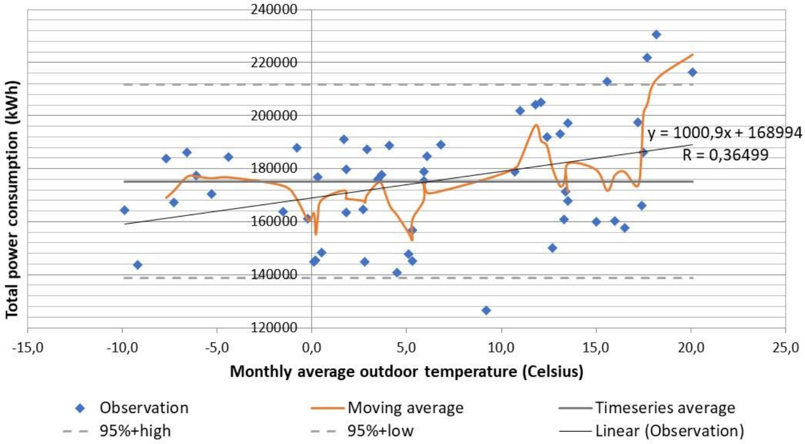


**Figure 14.** The five-step moving average on power consumption and average outdoor temperature [Publication I].

M. Wahlroos simulated waste heat utilization using EnergyPRO software on a laptop. EnergyPRO was suitable for analysis, as it is possible to analyze CHP plants and heat-only boilers (HOB). EnergyPRO is an input/output simulation tool, taking into account e.g. heat production plant characteristics, fuel prices, electricity prices, heat demand, ambient temperature, and DH network temperatures. EnergyPRO calculates the optimal DH operation strategy. Wahlroos carried out simulations by using the hourly resolution and simulating one year at a time. Years 2013 and 2015 with different characteristics were selected for the simulations. The reason for the selection of two separate years was to analyze cases with different outside temperatures and electricity prices. Waste heat was simulated in EnergyPRO either as a single aggregated heat production plant, or utilized waste heat was subtracted directly from heat demand depending on the scenario in question. The temperature of waste heat from DCs was assumed high enough to be able to feed waste heat directly to the supply side of the DH network, without priming the heat. Naturally, there would be an effect on the cases if priming would be used, as it requires electricity.

The marginal cost scenarios showed that during most hours, the waste heat was utilized to its full capacity in DH production. The non-utilization hours were only a few consecutive hours during the simulated period. In 2015, with lower electricity prices, 99% of available waste heat was utilized. In 2013, waste heat was utilized less due to higher electricity prices, and thus CHP production was a favorable source of heat. With the current pricing system, the majority of the heat was utilized even with a high capacity situation. This suggests that the proposed marginal cost pricing structure was at least profitable for the DH network operator.

When 100% of the waste heat was utilized, the reuse affected the CHP and heat pumps (only in 2013) the most by decreasing their utilization rates even further. On a few occasions in the scenarios, waste heat production satisfied the entire DH demand and even resulted in surplus heat. Without the possibilities to store the heat, the excess waste heat could not be utilized.

One of the most critical issues in utilizing waste heat is the potential savings in heat production costs. Waste heat utilization decreased the operation of CHP and profits from electricity sales. This was more apparent in 2015 when low electricity prices resulted in less profit. The results from the simulation showed that increased waste heat would result in savings in total production costs. The results also showed that waste heat utilization affected operations of other production units, but from the system perspective, increased utilization was profitable in any case.

The publication I provides more details on the simulation and results.

## 3.3 Waste Heat Utilization Investment Assessment

For NPV modeling in Publication V, the following assumptions and simplifications were made: 1) a typical rate of return factor for a similar venture was 15% [103], 2) a 10-year depreciation plan for the waste heat capturing and heat pump devices, 3) change in working capital was not relevant, 4) annual growth rate of power consumption decrease per rack was considered zero, 5) ramp-up time from initial capacity to full capacity was 24 months, 6) nominal cash flows were used for estimation, 7) tax rate was OECD average 22.34% and tax-shield was not used, 8) the measured power consumption of 4.286 kW per rack was used for each case, 9) heat recovery rate was fixed at 97%, 10) employer costs, on top of monthly salaries, were OECD average 14.4% [106], 11) COP of 3.75 was used for priming the heat, 12) the average salary annual base growth was 0.6% [107], 13) a maintenance specialist's monthly salary was 4000 €, and 14) a business manager's monthly salary was 6000 €. The phases of the NPV model are presented in Figure 15.

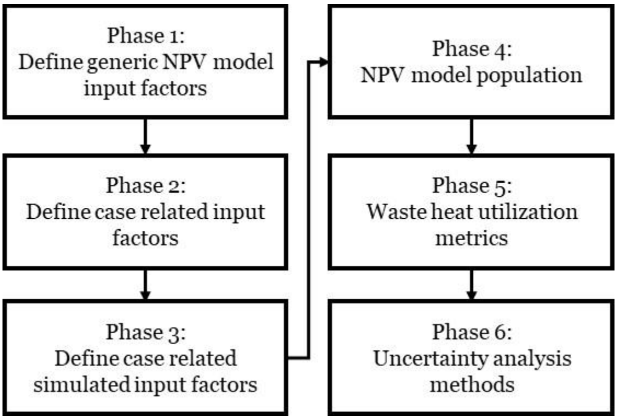


**Figure 15.** NPV model phases [Publication V].

The investment assessment included three cases. The first case was a small DC with a maximum capacity of roughly 50 racks, representing a typical small-scale service provider DC or a local DC of a multinational company with a variety of digital services hosted and managed. The second case was a medium size DC with 500 racks, representing a typical service provider DC, serving multiple customers with infrastructure as a service (IaaS), platform as a service (PaaS) and software as a service (SaaS). The third case was a large DC with a maximum capacity of 5000 racks, representing a large service provider DC offering colocation, IaaS, PaaS, and SaaS on an industrial scale for multiple customers and other service providers. All cases were assumed to start as a greenfield DC with a space utilization rate of 20%, growing to the maximum capacity within 24 months linearly, with a fixed monthly growth rate of 7.25%.

An investment into waste heat recapturing equipment includes the following components: 1) heat reuse equipment, 2) a connection to a DH operator, 3) setup project, 4) piping, and 5) heat pumps. In the small case, according to a 2018 interview with Mr. Porkka and Mr. Niiranen from Calefa Oy, a small 80 000 € heat reuse device is enough. According to Calefa Oy, in larger cases, there is a marginal capacity increase between each 2MW of rack power consumption. After each 2MW capacity increase in racks, a new block needs to be added. In the medium case, the 2MW block is invested immediately, and the total investment was 775 000 €. In the large case, the investment is divided over two years and aligned with the ramp-up time, bringing the total investment to 7 370 000 €. The connection to a DH operator is a significant source of uncertainty. A close connection between a DC and a DH operator was assumed. In demanding urban environments, setting up a connection can total hundreds of thousands of euros when streets need to be opened. In rural areas, transferring heat over long distances can become inefficient and costly.

The project costs are estimations by Calefa's reference projects. Projects depends on DC and many other variables, and are a source of uncertainty. The level of project uncertainty increases as the size of the DC increases. Waste heat reuse requires piping for the devices; we used prices for piping based on Calefa's references. The prices for heat pumps are estimated similarly to heat reuse devices; every 2MW adds a new block. The small case can utilize smaller devices. The equipment prices contain uncertainty. According to Calefa Oy, retrofitting an old DC with waste heat capturing capability is typically a similar investment compared to a greenfield DC.

A comprehensive sensitivity analysis to meet the validity objective of the results was conducted. The aim was to identify the critical parameters influencing the decision-making process and to quantify the degree of influence [108].

The simultaneous effect of variability, to the NPV model, of the five most significant factors was investigated with a Monte Carlo simulation. The simulation was coded with Python. A simplified NPV model for the simulation was used. The most significant factors were heat price, electricity price, COP, the rate of return and total investment. The Expected scenario values were used as input for the simulation. The following simplifications were made to the NPV model: 1) tax shield was not used, 2) all values were averaged and aggregated to year level, 3) the four separate parts of the investment project were aggregated to one total investment, 4) ramp-up time was taken into account as an average number of racks during a 10 year period, and 5) the medium case was used to populate other case-specific factors with multipliers to two remaining cases.

The simulation was run for 3 million rounds on a laptop running Jupyter Python software. Utilizing averages across the time frame benefits the revenue during ramp-up time, thus gives a penalty for costs. The rate of return has a more significant effect as time advances, thus creating small uncertainty to the distribution. The distribution of each case is within the Min and Max of the range for the scenario.

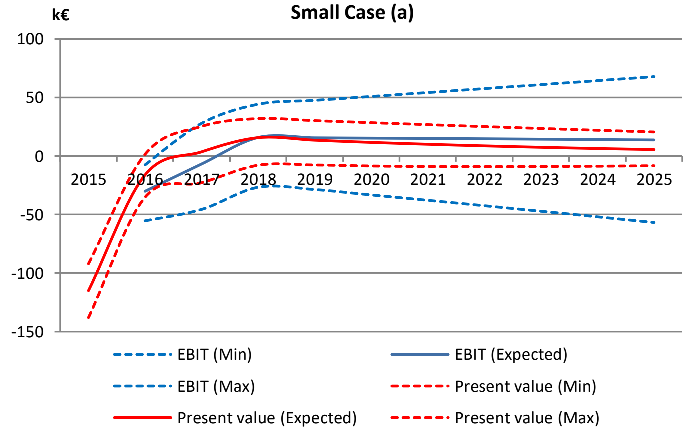
To strengthen the analysis, ROI percentages were also calculated. The results of the NPV model show that the small case appeared to create a negative NPV, indicating an unprofitable investment with the assumptions and inputs given to the model. Both medium and large cases gave a positive NPV. Nevertheless, the small case had a positive ROI, indicating the case being sensitive to changes in input variables, such as the rate of return factor. The IRR of the small case was 7.05%, which was below the expected rate of return. It should be noted that IRR must be above the company weighted average cost of capital (WACC), preferably above the rate of return.

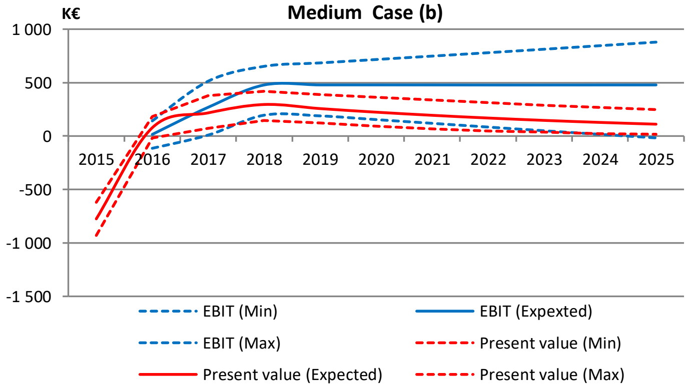
The PB period in the small case was over ten years, which was set as the scope of the assessment. All factors were set to minimum and maximum to investigate the investment KPI range. The total uncertainty in the small case [Min, Max] was [322%, -458%]. The negative NPV in the Expected scenario provided non-intuitive results (i.e., negative values for Max scenario). The uncertainty is considerable, and the small case was sensitive to input factor variation. Similarly, both the medium [-148%, 130%] and large [-87%, 75%] cases implied improved sensitivity against uncertainties when DC size increased. The medium case had a positive NPV in the Expected and Max scenarios. The large case was positive even in the Min scenario. The PB period for medium and large cases varied from 1.82 to 5.14 years depending on the scenario and case. The ranges of investment assessment KPIs are presented in Table 2.

**Table 2.** KPIs for each scenario [Publication V].

| | Scenario Min | | | Scenario Expected | | | Scenario Max | | |
|---|---|---|---|---|---|---|---|---|---|
| KPI | S | M | L | S | M | L | S | M | L |
| NPV (thousand euros) | -264.1 | -332.0 | 4120.0 | -48.5 | 1041.4 | 16329.2 | 143.8 | 2569.0 | 30152.6 |
| ROI | -309% | 51% | 419% | 56% | 412% | 1046% | 408% | 885% | 1892% |
| IRR | NA | 8.01% | 30.29% | 7.05% | 38.57 | 58.54% | 34.71% | 67.12% | 92.89 |
| PB (years) | >10 years | >10 years | 5.14 | >10 years | 3.72 | 2.75 | 4.11 | 2.14 | 1.82 |

The discounted cash flows (DCFs) and earnings before interests and taxes (EBIT) for each case with Expected, Min and Max scenarios were analyzed to visualize the effect of uncertainty in results as a function of time. Figure 16 shows the increasing uncertainty as a function of time. The variation between Min, Expected, and Max scenarios were large. In the large case, all KPIs were positive in all scenarios; it was not sensible to input factor variation from the investment decision-making perspective. Figure 17 summarizes different KPIs between scenarios and cases.





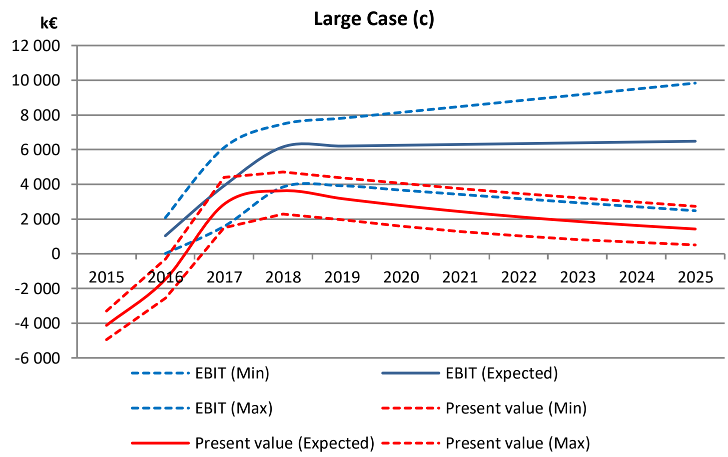
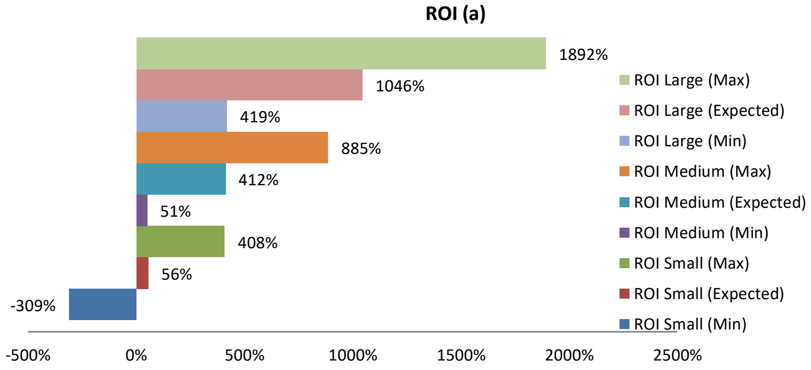
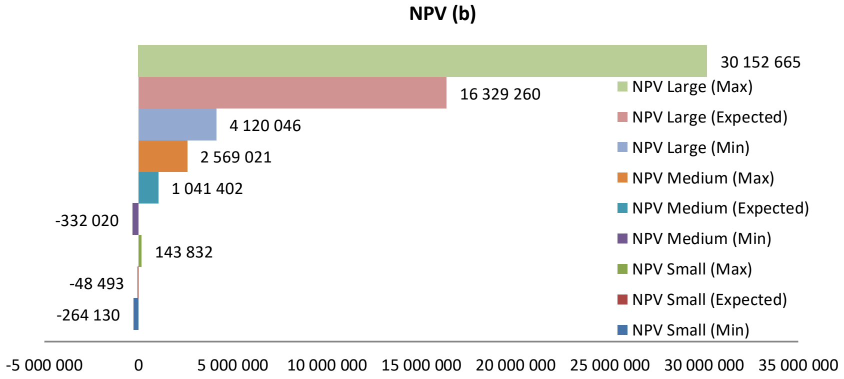


**Figure 16.** Min, Max and Expected scenario EBIT and PV with uncertainties in different cases (a-c) [Publication V].





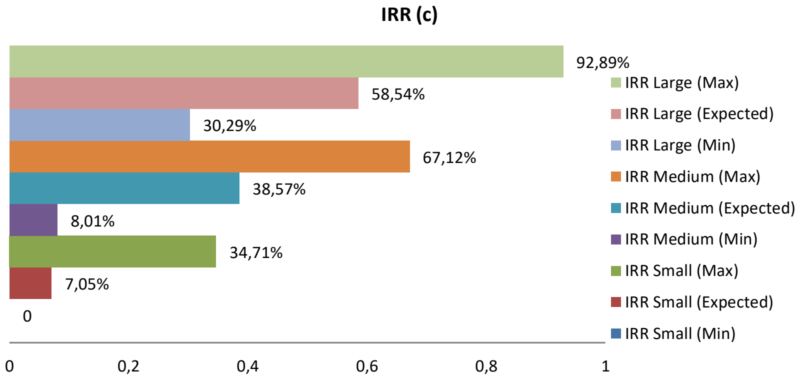


**Figure 17.** Min, Max and Expected scenario ROI (a), NPV (b) and IRR (c) with uncertainties [Publication V].

Table 3 presents energy efficiency metrics in different cases. The initial PUE values for the DCs without waste heat utilization were taken from the literature. Small, medium and large cases were considered to have initial PUE values of 2.2, 1.97, and 1.72, respectively. Electricity consumed by a heat pump increases the total power consumption of a DC. ERF values for DCs vary between 0.5–0.62, which indicates that over 50% of the total energy consumption could be recovered.

**Table 3.** Energy efficiency metrics in the case of waste heat utilization [Publication V].

| | Small case PUE 2.2 | Medium case PUE 1.97 | Large case PUE 1.72 |
|---|---|---|---|
| PUE with waste heat utilization | 2.48 | 2.23 | 1.98 |
| ERF | 0.5 | 0.55 | 0.62 |
| ERE | 1.25 | 1 | 0.75 |

The combined impact of the most significant factors in the NPV model was investigated with a simplified Monte Carlo simulation by randomizing the five factors under investigation. The simulation tool is available for everyone at GitHub [109]. The five identified factors with ranges [minimum, maximum, step] were: heat price €/MWh [36.7, 55.1, 10], electricity price €/MWh [64.5, 96.8, 10], rate of return [0.18, 0.12, 0.001], total investment factor [0.8, 1.2, 0.01] and COP [2.813, 4.687, 0.1]. The total number of possible permutations was approximately 255 billion. The simulation included 3 million rounds, approximately 1 million rounds for each case. The Monte Carlo simulation NPV distributions for all cases have been presented in Figure 18.

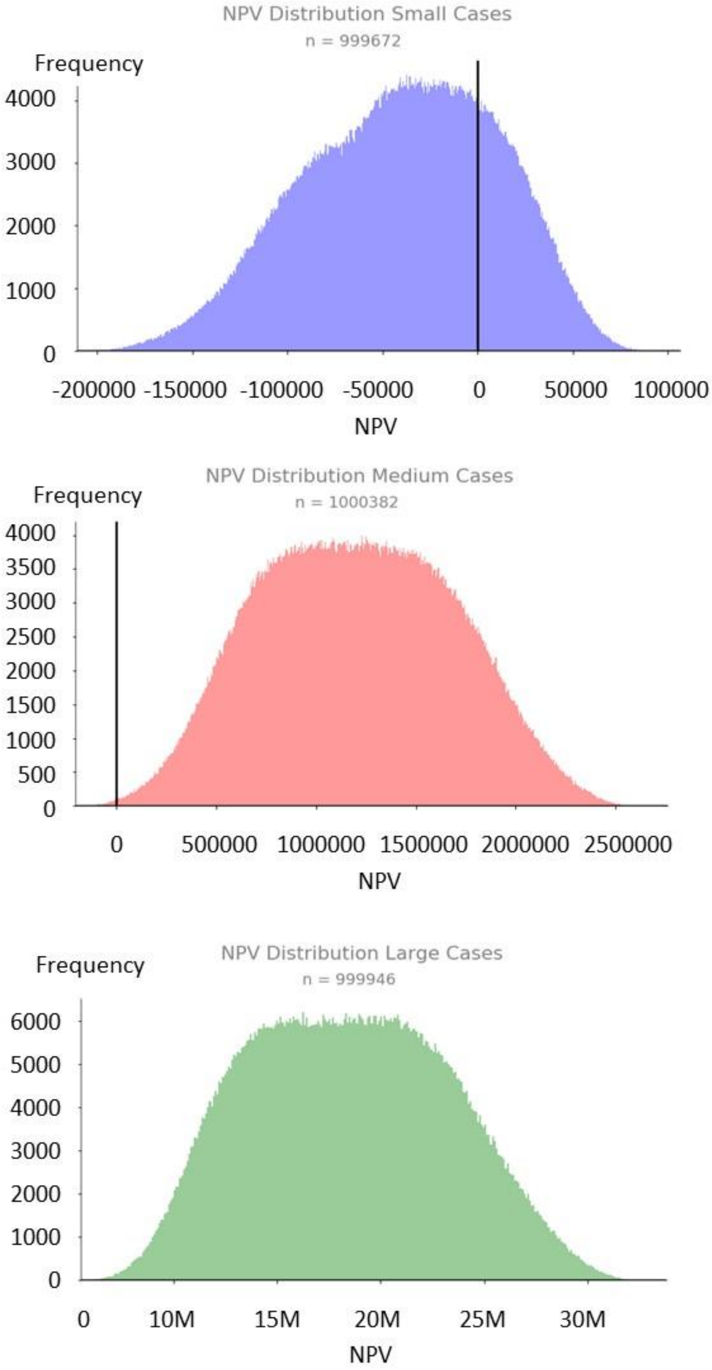


**Figure 18.** Monte Carlo NPV distributions for cases [Publication V].

The small case NPV output was negative with significant probability. All distributions followed normal distribution to a large extent. The expected value of normally distributed results is the mean of the results as *n* approaches infinity. The expected value of distribution in the small case is -40.04 k€ with the standard deviation of 50.79 k€. These results were aligned with the Min and Max scenarios for the small case. The expected value of the simulated small case was 8445 € higher than in the Expected scenario, which was understandable as only the five most significant factors were simulated. Also, the range of simulated results was within the Min and Max scenarios. Similar results apply to all cases. Table 4 presents the key characteristics of simulations for all distributions.

**Table 4.** Distribution characteristics [Publication V].

| Distribution | n | Min | Max | Mean | Standard deviation |
|---|---|---|---|---|---|
| Small case | 999 672 | -210 649 | 91 747 | -40 048 | 50 785 |
| Medium Case | 1 000 382 | -204 031 | 2 620 834 | 1 203 092 | 487 299 |
| Large case | 999 946 | 5 523 535 | 32 483 519 | 18 462 779 | 4 868 941 |

## 3.4 DC Waste Heat Utilization in Nordic Countries

In this section, some of the most interesting DC projects and DCs that utilize waste heat in the Nordic countries are presented. In Publication II, this part was mainly written by co-author M. Wahlroos. All data was derived from public sources. Many DCs have revealed very little information on the actual DC load or reused waste heat [110]. In addition, few large-scale DCs have been built in Finland, which does not utilize waste heat. Instead, free cooling has been chosen as a cooling option rather than connecting to a DH network. Table 5 presents some of the most promising DC projects from a waste heat utilization perspective. A more detailed description of the projects can be found in Publication II.

**Table 5.** DC projects considering waste heat utilization in the Nordic countries [Publication II].

| DC operator | Location | IT load capacity | Cooling technology | Waste heat reuse | Estimated recovered waste heat |
|---|---|---|---|---|---|
| Apple | Viborg, Denmark | Unknown, (floor area 166 000 $m^2$) | Free cooling | District heating | Unknown |
| Bahnhof (3 operational + 1 under construction) | Stockholm, Sweden | ~3 MW (21 MW under construction) | Heat pumps | District heating | 600 kW (Pionen) +<br>500 kW (St Erik) +<br>1500 kW (Thule) |
| CSC | Kajaani, Finland | 2.4 MW | Free cooling | Other processes | Unknown |
| TeliaCompany | Helsinki, Finland | 24 MW | Unknown | District heating | 200 GWh/a |
| TelecityGroup (5 locations) | Helsinki, Finland | 7 MW (2 MW reusing waste heat) | District cooling (+free cooling) | District heating | 4500 block apartments + 500 detached houses |
| Tieto | Espoo, Finland | 2 MW, (floor area 1000 $m^2$) | Heat pumps | District heating | ~30 GWh/a (~1500 detached houses) |
| Yandex | Mäntsälä, Finland | 10 MW | Free cooling | District heating | ~20 GWh/a (~1000 detached houses) |

One conclusion was that the business models are not explicit, and as the DC owners are typically not acting in the energy sector, the lack of know-how may prevent taking the risk of investing in waste heat utilization equipment. The negotiation process between DH and DC operators should be as transparent as possible for both parties.

In the negotiations, a win-win situation should be obtained between the DC operator and the DH network operator. Table 6 summarizes the requirements and benefits of waste heat utilization.

**Table 6.** Requirements and benefits in utilizing waste heat [Publication II].

| DH network operator | DC operator |
|---|---|
| • A stable source of heat and long-term contracts<br>• Quality of heat (temperature and timing)<br>• Possibility to replace DH peak production or remove the need for new capacity investments<br>• Decreasing DH production costs<br>• Fewer fossil fuels required to fulfill the DH demand | • Ease of use<br>• Transparency in pricing and investments<br>• Green image (higher ERF)<br>• Possibility to utilize district cooling |

The critical question for both parties is who investment in the heat capturing solution. Stenberg (2015) studied both alternatives, and although the results suggested that if the DC operator invests, it was more beneficial for the DC operator. Thus, the difference in the TCO was not significant [86]. It must be noted that the win-win situation may be further exploited if the DC is cooled by district cooling and the infrastructure is already inbuilt. Therefore, the decision on investing in waste heat recovery should be conducted in the planning phase of DC construction.

## 3.5 Critical Success Factors in Waste Heat Utilization Projects

Kotter (1995) introduced an effective eight-step change process [111], and the framework can be used to overcome waste heat utilization projects obstacles systematically. Further details of the process can be found in Publication II.

### Step 1: Create a Sense of Urgency

A sense of urgency is created around the need for change. If people start talking about the change, the urgency can build and feed on itself [111]. The CSFs for step 1 are; 1) clear communication regarding potential threats, opportunities and possible future scenarios, 2) honest discussions in a society with dynamic and convincing reasons as input, 3) support from stakeholders to strengthen the argumentation, and 4) actual results from working solutions to strengthen the message [111].

The magnitude of energy consumed by ICT is a function of an exponentially growing demand outstripping the energy efficiency gains made by the ICT industry. High energy consumption results in substantial electricity costs and high $CO_2$ emissions. These form an essence of the sense of urgency for change required in ICT energy consumption.

### Step 2: Form a Powerful Coalition

The aim is to convince people that change is necessary. It requires strong leadership and visible support from regulative authorities, academia, and organizations. The change coalition needs to work as a team to build urgency and momentum around the need for change [111]. The change coalition is required for overcoming barriers and obstacles. The CSFs for step 2 are; 1) identifying key stakeholders and leaders in a society and from organizations, 2) emotional commitment from key people, 3) team building within a change coalition and 4) performing an analysis of the weak areas of the change coalition and ensuring a mix of people from different stakeholders and different backgrounds [111].

There are challenges the change coalition must solve. It must answer to multidimensional questions such as: who has a problem with energy efficiency and why; who is responsible for energy efficiency and waste heat utilization; who has the incentive to lead the change; who are the stakeholders; and how to create a shared vision where everybody wins. To be successful in leading a change, communication and public relations must be seen as strategic assets to emphasize the cause. The change coalition must understand market conditions and program implementation obstacles. This understanding is essential for effective program planning and for developing reasonable forecasts for energy savings. Common obstacles for DC programs are; 1) technical complexity, 2) long lead times, 3) product production cycles associated with DCs, and 4) risk of a free-ridership. All elements of DC operations are technically complex with the goal of ensuring reliability [112].

### Step 3: Create a Vision for Change

The ideas and concepts need to be linked to a vision that society and stakeholders can grasp quickly and remember. A clear vision helps everyone to understand why they need to act [111]. The CSFs for step 3 are; 1) determining the values critical to a change, 2) a summary which captures the future vision, 3) a strategy to execute the vision, 4) ensuring, the change coalition can describe the vision in five minutes [111].

An inspiring vision could be formed around nZEB. The actualization of nZEB vision requires a fully integrated energy strategy, including aggressive reuse of waste heat [97]. Focused attention on creating national energy efficiency and waste heat reuse strategy is required. It must be enforced by regulatory supervision. There are two kinds of energy consumption reductions: 1) reductions that avoid energy consumption, but do not reduce power capacity requirements (temporary consumption avoidance), and 2) reduction of installed power capacity (structural consumption avoidance) [113]. Both should be part of the intended vision.

### Step 4: Communicate the Vision

Activities after the initial creation of the vision will determine the success of the change. The vision needs to be present daily in decision-making and problem-solving. A demonstration of outcomes and results is a way to convince the public about the vision [111]. The CSFs for step 4 are; 1) public discussion about the change vision, 2) openly and honestly addressing concerns, 3) applying the vision to all aspects of operations and tying everything back to the vision, and 4) leading by example [111].

There needs to be an open discussion about the sustainability of IT and energy efficiency, including waste heat recovery. The empowering vision must be communicated so that it reaches influential people and business decision makers; ultimately consumption dictates the demand for services. The vision could start to realize itself once the demand for sustainable ICT emerges, instead of the lowest possible price. Joint efforts with governments, municipalities, regulators, and companies ensure the vision has a strong change coalition behind it.

### Step 5: Remove Obstacles

At this step, the vision has already been communicated, and buy-in from all stakeholders has been achieved. A structure for the change needs to be put in place, and possible barriers periodically evaluated. Removing obstacles empowers people to execute the vision [111]. The CSFs for step 5 are; 1) identifying, or hiring, change leaders whose primary role is to deliver the change, 2) investigating organizational structure, job descriptions, performance, and compensation systems to ensure they are in line with the vision, 3) recognizing and rewarding people for making the change happen, 4) identifying people who are resisting the change, and helping them to understand what is needed, and 5) taking action to remove barriers (human or otherwise) rapidly [111].

An obstacle in waste heat utilization projects could be for example lack of interest from local municipality or company management team for waste heat utilization. The low-quality of the DC heat, transparency issues in pricing, and unclear business models can also be seen as obstacles. A strong change coalition will help in removing obstacles.

### Step 6: Create Short-Term Wins

Without wins, critics and negative thinkers might hurt progress. Therefore short-term targets are needed. A change team may have to work hard to come up with these targets, but each "win" that is produced can further motivate stakeholders [111]. The CSFs for step 6 are; 1) identifying projects that can be implemented without help from any influential critics of the change, 2) early targets that are expensive must not be chosen as justification of the investment, 3) thoroughly analyzing potential pros and cons of targets, and 4) rewarding people who help to meet targets [111].

An increase in energy efficiency is achieved with active thermal management strategies. Thermal management reduces OPEX of a DC [55]. Heat minimization is a valid target for any DC and provides short-term wins. Excess heat damages hardware as well as decreases energy efficiency. Regardless of heat level, the closer a cooling solution is to a heat source, the more effective the cooling is. The more effectively cool air is delivered to a server, and hot air is transferred back to a CRAC unit, the better the heat transfer is, thus resulting in higher energy efficiency [114]. Implementing energy efficiency metrics, presented in

Section 3.1.5, visualizes the effects of change, provides transparency, and provides possibilities to set short-term objective targets for change.

**Step 7: Build on the Change**

Launching one new initiative using a new system is excellent, but launching ten initiatives means the new system is working [111]. The CSFs for step 7 are; 1) after every win, analyzing of what went right and what still needs to be improved, 2) setting goals to continue building on the momentum already achieved, 3) learning Kaizen methodology, an idea of continuous improvement, 4) keeping ideas fresh by bringing in new change agents and leaders [111].

**Step 8: Anchor the Changes into Culture**

Finally, to make any change lasting, it should become part of the core of an organization. The culture of a corporation often determines what gets done. Support from leaders, including existing and new leaders, is valuable [111]. The CSFs for step 8 are; 1) discussion on progress of the change is needed, success stories, and repetition of the other stories that are heard, 2) including change ideals and values when hiring and training new staff, 3) publicly recognizing key members of the original change coalition, and making sure rest of the people remember their contributions, 4) plans to replace key leaders of change need to be in place, as they move on. These plans will help in ensuring that their legacy is not lost or forgotten [111].

## 3.6 Discussion

By investing in waste heat reuse, DCs can become more energy efficient. Green DC can be obtained with outdated high energy consuming equipment by utilizing on-site or off-site renewable energy sources combined with waste heat reuse. A service provider DC typically has several local and global customers, resulting in server activity across the day. In addition, during off-peak times backups are taken from servers and VMs. Virtualization further spreads workloads across servers. Based on the nature of a service provider DC, measurements and statistical analysis of one service provider DC suggests that the energy consumption is close to a uniformly distributed load profile. Naturally there can be configurations and service providers where this is not the case. In addition, a longer measurement period could have strengthened the conclusion. Risk of the variance in the availability of waste heat can be pooled. DH operators need many DCs to mitigate the risk of variance. Nonetheless, a DH network cannot rely solely on the waste heat from DCs.

The pricing structure must be mutually beneficial so that the interest to sell and buy exists for respective parties. The pricing structure must also be transparent and above all predictable to analyze benefits and profits in the long term.

Investment-decisions depend on the risk of the project and estimated future cash flows. The profitability of the waste heat recovery investment was positive inside the full range of uncertainty in the large case. In the medium case, the extremely pessimistic factor values resulted in a negative NPV. Nevertheless, even in the pessimistic scenario, the IRR was 8.02%, which is higher than the WACC in many companies. Therefore, the investment could still be worthwhile from ecological sense. The small case seems problematic. The Expected scenario NPV value was negative; the Min scenario was hugely negative. Only the extreme Max scenario factor values resulted in a positive NPV. The small case was susceptible to factor variations. Therefore, it was challenging to make an investment assessment on the small case. It contained risk. In the model, all waste heat was assumed to be sold to a DH operator. In the small case, alternative customers for waste heat could be considered.

The heat price was one of the most critical factors in the simulations. As it was estimated that heat would be priced with marginal cost based pricing, the results may differ from the actual heat prices offered by the energy companies. The actual heat prices might be far lower if the energy companies try to take advantage of the waste heat provider.

The electricity price was another critical factor based on the uncertainty analysis. Electricity prices were estimated to decrease based on the current trend, although some studies have suggested growing electricity prices, at least on the small consumer side. Especially, electricity transmission prices are likely to increase in the future due to legal obligations for transmission system operators to invest in the security of electricity transmission according to the Electricity Market Act, which was implemented in 2013 [115], [116]. The small case was sensitive to input factor values. A simulation with employees set to zero was done. The small case resulted in a mean NPV of 79 500 € with results ranging from -60 000 € to 222 000 €. From these results, the conclusion is that the small case was more dependent on fixed costs compared to the two other cases. The number of employees needs to be evaluated with consideration, as the impact on the distribution results was high.

Both ERE and PUE are generic metrics and not enough for engineering analysis purposes. To gain further insight into the specifics of thermodynamics and energy efficiency, new metrics were suggested to complement ERE and PUE. From 64 relevant publications, 37 energy efficiency metrics were discovered, and 13/37 suggested. Suggested metrics include PUE, ERE, power density efficiency (PDE), return temperature index (RTI), supply heat index (SHI), return heat index (RHI), performance per watt (PPW), workload power efficiency (WPE), network power usage effectiveness (NPUE), system power usage effectiveness (sPUE), DC workload power efficiency (DWPE), fixed to variable energy ratio (FVER), and DC energy productivity (DCeP). Together these metrics create a holistic view on DC thermodynamics and provide data for waste heat reuse decision-making for DC operators. DH operators gain actual data for forecasting available waste heat as a function of time.

ERE will be a fundamental tool as industrial and commercial buildings with DCs move towards nZEB targets. Whether the building achieves this or not shortly will likely be primarily dependent on the size of the DC. Current on-site renewable energy sources are often somewhat higher in cost than standard electrical grid prices, and for the very large DCs, this will slow the movement towards nZEB. [97]

# 4. Online Advertising

Online advertising is part of the Internet ecosystem and services. Online ads are almost indistinguishable to end-users but consume a significant part of the resources. Ads are also a significant source of income for companies providing "free" Internet services.

In this chapter, the environmental impact of online advertising is assessed, and the proportion of $CO_2e$ emissions resulting from ad fraud is identified. This chapter also introduces blockchain as one possible solution to the ad fraud problem. The results and findings in this chapter are from Publications III and IV.

Section 4.1 provides a literature review on the methods for assessing an environmental impact and introduces the new framework, from Publication III, for conducting an EIA for any Internet service, online advertising is used as a case example. Section 4.2 presents the results from Publication III and reveals the energy consumption and $CO_2e$ emissions of online advertising and ad fraud. Section 4.3 introduces and evaluates blockchain technology's potential to reduce ad fraud. Lower ad fraud rate would improve the environmental impact of online advertising. The results are from Publication IV. Section 4.4 discusses the findings.

## 4.1 Literature Review

Online advertising can be divided into two concepts; traditional online advertising and programmatic online advertising. Traditional online advertising is used by large advertisers and publishers with the financial leverage to commission an advertising agency. Programmatic online advertising is designed for small advertisers and publishers to ease the access to the online advertising market. The programmatic model enables dynamic advertising budget allocation with the desired context of publishers, and targets a specific audience efficiently [117].

Programmatic online advertising has a disadvantage of being exposed to ad fraud. Programs can easily exploit the common event-based pricing model. Detection of ad fraud is a challenging task due to the large volume of transactions [117].

The capacity to connect hundreds of thousands of publishers with a similar number of advertisers in an automated manner and the promise of accurately targeted advertising have caused digital marketing to rapidly evolve into a complex ecosystem where different intermediaries are focused on optimizing particular functions. This ecosystem operates effectively as a black box for the principal parties: advertisers, publishers, and users.

The online advertising ecosystem has become infested with thousands of intermediaries, whose business models range from exploiting user data, to verification companies promising to help advertisers secure their advertising budgets. The principal parties in online advertising have recently all pointed out concerns related to intermediaries, the actual value they provide, and how in many cases these intermediaries operate against their interests. Advertisers are concerned about ad fraud [78] and ad misplacement, publishers are concerned about their diminishing share of advertising budgets [118], and users are concerned about their right to privacy [119].

Self-regulation of the online advertising industry has not succeeded in mitigating ad fraud.

### 4.1.1 Methods for Assessing Environmental Impact

There are three main assessments regarding the environment: 1) life cycle assessment (LCA), 2) impact assessment (IA), and 3) environmental impact assessment (EIA).

LCA is a systematic and transparent method for assessing environmental impacts associated with the creation, use, and disposal of products and systems, from the cradle to the grave [3], [4], [30], [120]. IA is defined as a technical tool for analyzing the consequences of a planned action [24], [26], [121]. IA reflects the positivist theory, or rationalism, implying better data leads to better decisions [121]. EIA is a catalyst for change [23] and a globally established multidisciplinary tool to promote sustainability [27], [122]. EIA predicts various impacts of a project on its surroundings. Impacts include biophysical, social and health environments [122].

The fundamental concepts of the impact assessments include the best practices, system boundary selection, allocation, and uncertainty analysis [22]. System boundary selection defines which devices, processes and activities are included in the assessment. A system boundary should be implicit [4]. With any complex assessment, like with assessing the energy consumption of the Internet, plurality is essential to gather the relevant sciences together to form an assessment containing aspects of social, moral, economic and ecologic points of views [121].

Allocation is a method for dividing the environmental burdens of a multi-functional process. Allocation can be done by sub-dividing burdens into sub-processes, based on physical relationships, or based on non-physical relationships. As an alternative, the product system can be expanded to avoid allocation altogether [4].

Uncertainties to any assessment can arise from the following reasons: 1) poorly measured data, 2) data gaps, 3) unrepresentative proxy data, 4) model uncertainty, 5) unobservable data, 6) outdated data and 7) methodological choices [4]. Impact assessments usually lack spatial variation and local environment data, and the effects are assumed to be global and homogenous, thus creating uncertainties [4]. For the Internet, globalism is natural as it has no national boundaries. However, when considering $CO_2e$ emissions created by the Internet, the local grid mix is a significant factor.

Most of the Internet IAs define a functional unit around a product. Only a few studies have been modeled around a service [4]. There are four methodological approaches to assess the Internet energy consumption: 1) top-down, 2) bottom-up, 3) model based, and 4) the unified method. The top-down methodology-based analyses require two distinct factors: 1) the energy consumption of the whole system or a part of the system, and 2) the total traffic associated with the system in question [20], [28], [123], [124]. The top-down methodology can produce a relatively large estimation error [20], [28], [32], [123] as it relates the total energy consumption of network devices to the total data volume. By addressing the entire population, the top-down methodology provides more robust results but cannot form future scenarios, as there is no relationship between network parameters and network energy consumption [32]. The bottom-up methodology is based on direct observations of one or more case studies generalized into total results [28], [121], [123], [124]. The methodology estimates energy intensity per network device class and aggregates results to all network devices of the end-to-end connection [20], [32]. The central assumptions are average energy consumption and data throughput per device class, and the number of such devices in the end-to-end connection [20], [28], [32]. The model-based methodology models parts of the Internet based on network design principles. Manufacturers' device energy consumption data is inserted into the model leading to total energy consumption, which is related to corresponding data [123]. Models rarely take relevant characteristics of an actual network, such as redundancy, cooling, power transmission, or over-provisioning, into account [20]. The unified methodology combines the top-down and bottom-up methods. In this methodology, the ratios are calculated top-down and result estimated from bottom-up for each sub-process, such as end-user devices, access networks or DCs in a reference year [20]. The unified method evaluates energy consumption characteristics and provides forecasts based on technology trends [20]. Several researchers have used the unified methodology [28].

Advancements in the ICT sector emphasize the ability to generalize from already conducted case studies. The combination of technological development and a massive number of different ICT products makes extrapolations and scaling from available data an attractive option [125]. Based on Arushanyan et al. (2014) review study; in the ICT domain, the manufacturing and use phases have the most significant environmental impact [125].

### 4.1.2 New Framework for Assessing Energy Consumption of Online Advertising

A stepwise framework for assessing the environmental impact of the Internet service locally or globally was created. The framework consists of eight phases, each phase containing a collection of best practices. Many fragmented best practices were gathered into the same environmental impact assessment framework.

The phases are presented on a more detailed level in the Publication III. The framework is presented in Figure 19.

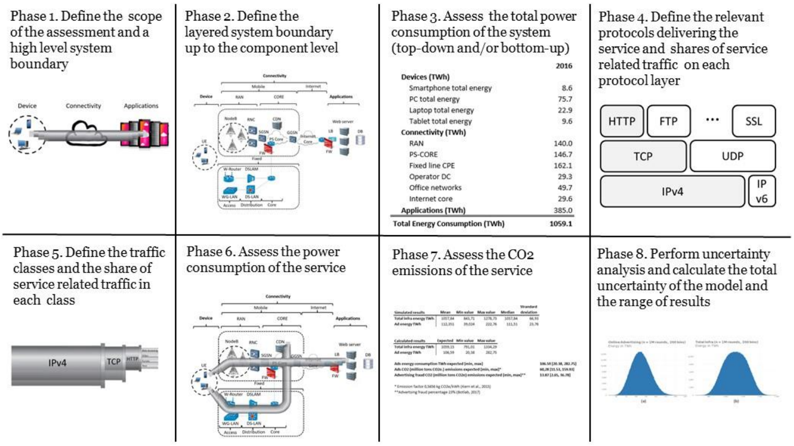


**Figure 19.** A framework for the EIA of the Internet service [Publication III].

All eight phases were used to assess the EIA of online advertising. A system boundary was created, energy consumption and shares of traffic with top-down or bottom-up methodologies were assessed, the peer-reviewed base values to the year 2016 were extrapolated, and the results were analyzed. The direct energy consumption was compared, excluding energy supply chains containing the supply of primary power, power plants, and grids bringing them to devices. An average German grid mix has been used when estimating the $CO_2e$ footprint. In the system boundary, mobile Internet was included, as it has an increasingly important role and its energy consumption has been significant [123]. In addition, the content delivery networks (CDN) have been considered, as they process services closer to the end users, thus have reduced the need for higher capacity in the Internet core. Comparisons to previous studies should be done with care, as the system boundaries vary between results [123].

The assessment is divided into four discrete analysis layers. The first layer is the energy consumption of the system boundary infrastructure. The second layer is the shares of access network traffic and the shares of Internet protocol (IP) delivering the service. The protocols were selected, as there is current, reliable, and measured data available. The third layer is the traffic classes representing end-user activity. The fourth layer is the share of individual services in each class. Each Internet service belongs to at least one of the classes.

## 4.2 The Environmental Impact of Online Advertising and Ad Fraud

The total energy consumption of online advertising (2016) for each traffic class, without uncertainties, was calculated in Publication III. The results are presented in Table 7.

**Table 7.** Energy consumption of online advertising (TWh) without uncertainties (2016) [Publication III].

| | Video | File sharing | Web, email, and data | Online gaming | Total |
|---|---|---|---|---|---|
| **Devices** | | | | | |
| Smartphone | 0.48 | 0.003 | 1.07 | 0.00 | 1.55 |
| PC | 3.62 | 0.62 | 3.20 | 0.09 | 7.53 |
| Laptop | 1.09 | 0.19 | 0.97 | 0.03 | 2.28 |
| Tablet | 0.46 | 0.08 | 0.40 | 0.01 | 0.95 |
| **Connectivity** | | | | | |
| RAN | 7.91 | 0.04 | 17.46 | 0.00 | 25.41 |
| PS-CORE | 5.43 | 0.83 | 5.63 | 0.11 | 12.01 |
| Fixed line CPE | 7.74 | 1.33 | 6.86 | 0.18 | 16.12 |
| Operator DC | 1.09 | 0.17 | 1.13 | 0.02 | 2.40 |
| Office networks | 2.37 | 0.41 | 2.10 | 0.06 | 4.94 |
| Internet core | 0.66 | 0.10 | 0.68 | 0.01 | 1.46 |
| **Applications** | 14.26 | 2.18 | 15.19 | 0.30 | 31.93 |
| **Total** | 45.11 | 5.96 | 54.70 | 0.82 | 106.59 |

With the presented framework, system boundary, base value estimations, and assumptions, online advertising energy consumption in 2016 was 106.59 TWh. Web-browsing was the dominant source of online advertising and therefore consumed the highest amount of energy.

There were uncertainties in the estimation. Uncertainty analysis indicates that the most influential infrastructure energy consumption input factors were applications, radio access networks (RAN), and personal computers (PC). Similarly, the most influential input factors for traffic were the share of ads in the fixed and mobile video traffic class, the share of ads in the fixed and mobile web, email and data traffic class, the share of transmission control protocol (TCP), and the share of hypertext transfer protocol (HTTP). An investigation into the output of online advertising energy consumption, when the input factors are randomly picked from the range of uncertainty for each input factor, was conducted on a laptop running Jupyter Python software. The distribution of outputs from a Monte Carlo simulation with one million simulated rounds is presented in Figure 20.

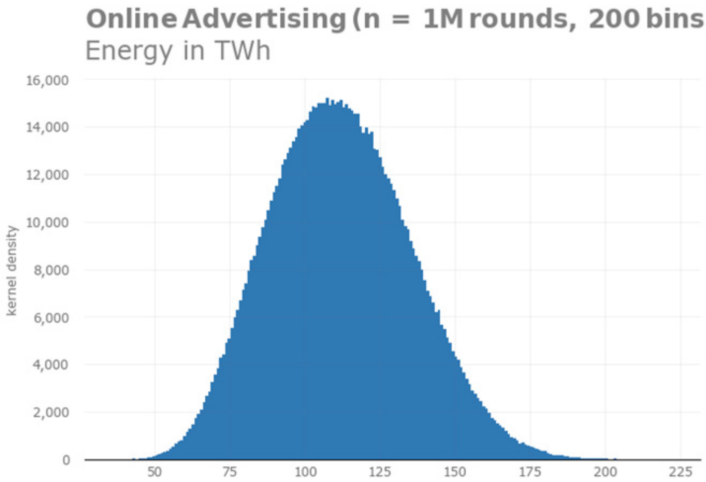


**Figure 20.** Online advertising energy consumption TWh distribution [Publication III].

The online advertising energy consumption distribution is a normal distribution; therefore, the mean value is also the expected value. The probability is more concentrated around the mean value in the distribution. The simulated results show 5 TWh higher mean values for online advertising, compared to the calculated results, because of the simplifications of the framework made in the simulation. The whole distribution is within the range of calculated results as expected. The results are presented in Table 8.

**Table 8.** The online advertising (2016) energy consumption and $CO_2e$ footprint [Publication III].

| **Simulated results** | **Mean** | **Min value** | **Max value** | **Median** | **Standard deviation** |
|---|---|---|---|---|---|
| **Total infra energy TWh** | 1057.76 | 838.96 | 1278.44 | 1057.79 | 66.95 |
| **Ad energy TWh** | 111.82 | 36.138 | 222.4 | 110.98 | 23.44 |

| **Calculated results** | **Expected** | **Min value** | **Max value** |
|---|---|---|---|
| **Total infra energy TWh** | 1059.15 | 791.01 | 1334.29 |
| **Ad energy TWh** | 106.59 | 20.38 | 282.75 |

| | |
|---|---|
| **Ads energy consumption TWh expected [min, max]** | **106.59 [20.38, 282.75]** |
| **Ads Mt $CO_2e$ emissions expected [min, max] *** | **60.28 [11.53, 159.93]** |
| **Ad fraud Mt $CO_2e$ emissions expected [min, max] **** | **13.87 [2.65, 36.78]** |

* German emission factor 0,5656 kg $CO_2e$ /kWh [29]

**Ad fraud percentage 23% [35]

The results must be viewed with uncertainties considered. In 2016, online advertising consumed 20–282 TWh of energy. With extrapolated 2016 input factor values without uncertainties, online advertising consumed 106 TWh of energy. Online advertising produced 60 Mt $CO_2e$ (between 12 and 159 Mt of $CO_2e$ when considering uncertainty). The share of ad fraud traffic was 13.87 Mt of $CO_2e$ emissions (between 2.65 and 36.78 Mt of $CO_2e$ when considering uncertainty).

Using the emission factor simplifies the calculation but at the same time creates uncertainties, as the grid mix varies between different geographical locations and as a function of time (there can be changes in the grid mix daily). For the purposes of the thesis, the average is sufficient. Online advertising $CO_2e$ emissions are 10% of the total infrastructure emissions and therefore a significant contributor to the environmental impact of the Internet ecosystem. Advertising fraud can be considered a total waste of resources, both economically and environmentally. The framework-based EIA of online advertising contains significant uncertainties but even with uncertainties included, the range of values indicates the consumption is significant.

## 4.3 Blockchain's Potential to Reduce Ad Fraud

In this section, blockchain technology is introduced. Secondly, the online advertising specific requirements to consider blockchain to become a functional solution are presented. The section ends with an analysis of commercially available blockchain solutions and platforms. The results are from Publication IV.

### 4.3.1 Blockchain Technology

The world is undergoing a rapid change. The change is accelerated by the development of Internet technology and the exponential growth of data. Blockchain could be the fifth disruptive technology after mainframes, PCs, the Internet, mobile communication and social media [126]. The blockchain is a distributed peer-to-peer database, which provides a technology for the decentralization of systems. Blockchain alone does not guarantee decentralization, but it guarantees the decentralization of data storages and transactions. The decentralized model has the potential for increased equality in storing, and availability of information and resources.

Blockchain can be utilized to facilitate transactions between nodes in the peer-to-peer network. What is transacted could be virtually anything; currency, votes, health data, ideas, predictions, storage capacity, computing power, or food, to name a few examples. So far, the emphasis has been on cryptocurrencies such as Bitcoin, and there has been less talk about the underlying innovation - the blockchain technology.  The initial coin offering (ICO) ecosystem has been noted, powered by another popular cryptocurrency, Ethereum, is rapidly shifting the focus, and new applications are introduced almost every week. Even though the blockchain technology promises to transform the human society in various ways, much work remains to be done before that promise translates into wide-reaching benefits for the average person. Today, the best-known successful new business models made possible by cryptocurrencies are malicious. Examples include ransomware attacks [127] and dark web markets [128] selling weapons, wholesale heroin [129], personal data, and murder-on-hire [130]. There are however many proven benefits from blockchain adoption, such as is the case with Bitcoin being used to reduce ad fraud [131].

The blockchain technology includes three essential components; 1) the application, 2) the protocol, and 3) the cryptographic solution. The basic principle of a blockchain is presented in Figure 21. A blockchain consists of blocks, hashes, and hash functions. The n-2 block on the bottom records its hash into the block. Also, the hash of the n-3 is also recorded to the same block. The inclusion of the previous block hash cryptographically ties the current block to the previous block forming a chain of blocks. A hash function is a mathematical algorithm that transforms input into an output. A cryptographic hash function can be complicated to revert. This feature of a blockchain is called collision resistance [132]. Every block includes the timestamp of its creation and additional information based on the configuration of the blockchain in question. All blocks have the payload of their block and all the previous blocks payload.

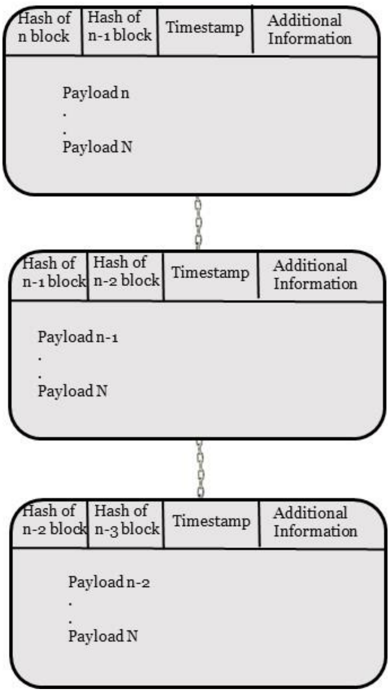


**Figure 21.** The basic principle of a blockchain [Publication IV].

The functionality of a blockchain can be described in the following way: The node sending new data records the data into a block and then sends a broadcast about the new available block to the blockchain network. The nodes receiving the new block verify the block from the hash. If the payload was correct, it is added to a block. Proof of work (PoW) or proof of stake (PoS) algorithm is executed to the block by all member nodes. The new block is added to the blockchain once a consensus is reached and all nodes verify the block [133].

One of the novelties of blockchain is the concept of "the miner" and how the miners unlock value in the blockchain - in the case of Bitcoin - by solving difficult computational problems. In blockchain storage, there is no double-send problem; each node is assigned with a private key and a public key. The fundamental functions of blockchain make it "trustless" in the sense that value can be exchanged with confidence without dependence on a trusted 3rd-party or central administration. Blockchain architecture generic benefits include; 1) decentralized processing, 2) redundancy, 3) immutable public record, 4) transparent access, and 5) global reach [132].

There are three different kinds of blockchains; 1) private, 2) public and 3) hybrid [134]. In an entirely private blockchain write-permissions are monitored by a centralized entity of decision-making and read-permissions are either public or restricted. A private blockchain amounts to a permissioned ledger, whereby an organizational process of know-your-business (KYB) and know-your-customer (KYC) enables the whitelisting (or blacklisting) of a user identity. Public decentralized blockchains are accessible to every Internet user. All members can determine what blocks are added to the chain and what its current state is. Fully decentralized public blockchains need a consensus mechanism for the validating process.

The main difference between public and private blockchains is the level of decentralization, or how they ensure anonymity. There is a continuum between the two extremes, resulting in partially decentralized blockchains. Consortium blockchains constitute a hybrid between the public and the single highly trusted private blockchain. The continuum is also applicable to energy consumption; public blockchains, especially those using the trustless PoW consensus algorithm, consume vast amounts of energy compared to a trusted private blockchain.

To provide the authenticity mentioned above and security properties, different implementations of blockchain protocols use different types of proofs. The most well-known proof is the one used in the context of Bitcoin, PoW. PoW was developed initially to defend from denial-of-service attacks and spam. The high total hash power of the blockchain network was needed to defend against a potential 51% of the network hash rate. All clients could perform hashing. In the advent of Bitcoin almost 15 years later, PoW proved to be an energy consumption nightmare as the race for mining profits begun. In 2012, the total performance of the Bitcoin network surpassed that of the most productive supercomputer in the world [135]. PoW protocols are slow [132]. The scarce resources required by PoW are CPU clock cycles and electricity [136].

To modify a block relying on PoW, an attacker or a would-be-abuser needs to mine all blocks previous to the one the attacker wants to alter. The cost of mining an individual block is exceptionally high since it is subject to computationally very costly operations, such as solving complex cryptographic puzzles. However, the high computational cost associated with the PoW paradigm is also the main drawback of the blockchain approach used in the context of Bitcoin. This is because the required complexity associated with mining a block requires enormous amounts of power and computation resources making the approach unsustainable in fields where scale is a concern. For fields such as online advertising, where scale is of great concern, PoW is not a suitable paradigm even for early-stage implementations.

The PoW based Bitcoin blockchain needs thousands of nodes and more than half a million dollars daily to secure one single cryptocurrency [137]. The challenge of blockchain consensus, which the PoW paradigms attempt to address, is that the distributed system must agree on a single shared state. The current consensus mechanism designs of blockchains are slow, time-consuming and energy inefficient.

Current PoW blockchain-based solutions offer poor energy efficiency when applied at a much lower scale than what online advertising would require. For example, Bitcoin proved to be an energy consumption nightmare, as the race for mining profits began. There is little available data on the energy consumption of alternative blockchain implementations with a scale even close to Bitcoin. To give some perspective, in 2015 Bitcoin mining used 982 MWh/day, which transforms into an energy cost of $15 million [126]. According to an article, energy consumption per Bitcoin was 240 kWh in 2014, and it has increased since then [138]. The average monthly growth of the Bitcoin network hash rate has been 37%, but it has slowed down as the price of Bitcoin has grown. In 2015, the Long Future Foundation presented a modelling tool showing that Bitcoin could one day consume up to 60% of global energy production, or 13000 TWh. Even in a conservative scenario of a 5% year-on-year growth, with half of the energy from fossils, over 4000 kg of $CO_2e$ per mined Bitcoin is produced [139]. In September 2017 the blockchain size was 125GB, and it grew by 35GB from September 2016 [140].

There are many alternatives to PoW. Thus it is unclear how their security properties and incentives hold in comparison. Alternatives include replacing crypto-puzzles used in PoW with meaningful problems, making power consumption less wasteful [141]. The primary consensus mechanisms are PoW, PoS, delayed PoW (dPoW), proof of burn (PoB), proof of capacity (PoC), proof of activity (PoA), proof of existence (PoE), proof of intelligence (PoI), proof of luck (PoL), ripple ledger, lightning network, and cross blockchains. Detailed descriptions of the aforementioned consensus mechanisms can be found in [142].

There are three different system architecture components that can be used when designing a blockchain based solution. The three basic ideas are presented in Figure 22. Information into a blockchain can be entered directly on-chain (a). Alternatively, information can be stored off-chain and transactions inserted into a blockchain (b). There can also be a trust relationship between a parent and a sidechain (c). Off-chain and sidechain concepts are explained in more detail in the following paragraphs.

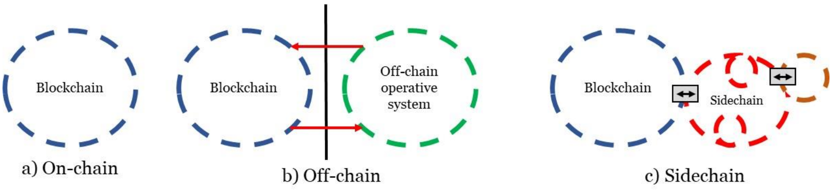


**Figure 22.** The basic idea of On-chain, Off-chain, and Sidechain [Publication IV].

Sidechain is a blockchain, which can validate data from other blockchains [143]. Sidechains extend the decentralization of trust to other digital assets. A sidechain is a separate blockchain, attached to the parent. Sidechains can be attached to the parent chain with a two-way peg [144]. The idea of sidechains is to avoid unnecessary trust on top of the parent chain [143]. Processing of transactions can also take place in permissioned and private sidechains. This allows transactions from one chain to be used in another separate chain and vice versa, securely. This is a more efficient and flexible consensus mechanism as sidechains can have substantially less significant nodes [145]. Such interoperable chains are called pegged sidechains [143]. Sidechain technology has been implemented to established blockchain platforms, but there are still challenges [144].

Off-chain applications provide real-time, verified transactions to all users of the application without transaction fees. This is achieved by committing transactions between users in a separate ledger [146]. Off-chain transactions have serious risks. Most off-chain systems require that the user trusts them. An off-chain system could be hacked, leading (among other things) to important economic losses [146]. It should be carefully considered when to use on-chain or off-chain transactions as both have pros and cons. There are trade-offs in both [146].

Distributed applications include a full application stack for accessing blockchains and off-chain solutions like databases and storage. Nowadays it is possible to store the records in a blockchain with smart contracts [145]. Depending on the smart contract solution, there are different rules on when to store in the chain, what kind of records are stored, and what is the data being stored. Smart contracts usually use application programming interfaces (API) to communicate with off-chain applications. This means that off-site data can be utilized efficiently [145].

Regardless of the way data is created, off-chain or on-chain errors affecting accuracy can occur. This is true for both single and multiple chain architectures. The inaccuracies in a blockchain are not easy to overcome. In a private and permissioned chain, the risk of a single party gaining majority of the tokens is higher. For instance, a concentration of nodes, adding a significant computing power altogether, could create collusion that affects trust, which is the basis of the blockchain technology [147].

### 4.3.2 Specific Requirements Related to Online Advertising

The requirements for an online advertising specific implementation of blockchain fall into two categories; those that are specific to online advertising (green in Figure 23), and general blockchain requirements (blue in Figure 23). In the following sections, a brief overview of the requirements presented in Figure 23 is provided.

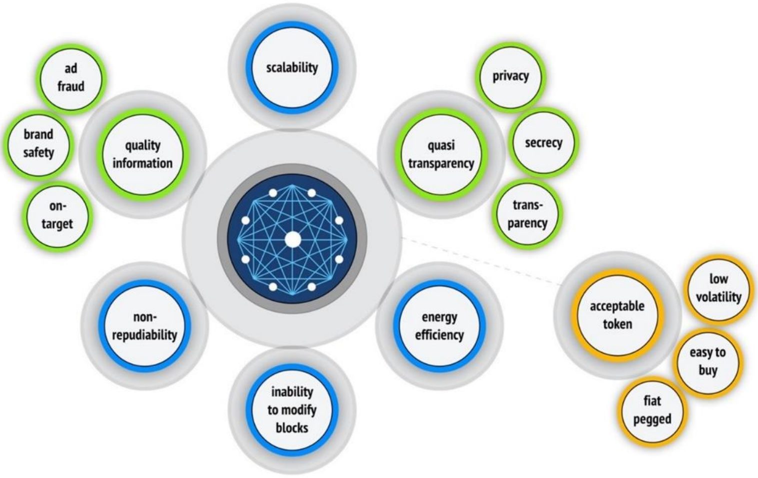


**Figure 23.** The main requirements of online advertising to blockchain technology [Publication IV].

**Scalability:** Scalability has been understood in the context of blockchain as the number of nodes able to participate in the peer-to-peer network but not in the rate of generated blocks. In other words, current blockchain implementations focus on on-demand authentication of transactions as opposed to managing a stream of transactions. While there are proposals for approaches claiming to scale to hundreds of millions of nodes, none of the existing models address the issue of scalability regarding the number of transactions at the scale of services such as online advertising. In the online advertising context, a specific stakeholder performs in the order of tens of millions to tens of billions of transactions per day. The transactions map into rates of hundreds to hundreds of thousands of transactions per second. Moreover, these blocks need to be created in real-time along with each completed transaction imposing scalability limitations not previously explored in the context of the blockchain. Existing proposals envision much lower rates of block generation which do not meet the demands of online advertising or fields with similar scale demand, such as equities trading.

In the previous paragraphs, the scalability related to the generation of blocks was discussed. However, a complementary problem is the validation of blocks. If validation is done offline, the scalability demand of the system is lower. However, if the validation is expected to be done in real time, the challenge is enormous, as chains need to be distributed in near real-time to all nodes in the network so that they can validate the blocks.

**Quasi-transparency:** Online advertising related transactions require anonymity whereas typical blockchain based systems do not, and they protect it whereas typical blockchain systems expose the identity. Every online advertising transaction must provide privacy, secrecy and transparency, all at the same time, for different data inside the transaction.

Conceptually, in blockchain protocols, the blocks form a distributed database including information about the transactions. The information is public for all nodes in the network. However, this principle would not apply to the online advertising industry. The information recorded in each transaction is considered sensitive by the creator of the block. It might, for instance, include financial information related to the transaction, the name of the publisher, or the name of the advertiser. In addition, factors such as user privacy and child protection should also be considered regarding data protection. Therefore, in order to develop a blockchain protocol suitable for the online advertising industry, the anonymity of sensitive information included in a transaction is a must-have feature. The requirement is not specific to online advertising but has far-reaching potential across a multitude of fields where authenticity is desired, but sensitive information cannot be compromised.

**Inability to modify blocks:** Blockchain protocols respond to the need of creating trustless systems where there is no need for third party verification of any kind. One of the fundamental properties guaranteeing trust is the inability of nodes to modify created blocks. In the case of Bitcoin, this is achieved through the PoW paradigm. Unfortunately, PoW is not providing the scalability to billions of transactions needed in the online advertising context. Alternative solutions need to be explored. In the case of online advertising, a technique guaranteeing the inability of block modification should be defined. At the same time, it should be scalable enough to meet the requirement of 10^11 to 10^12 transactions per day.

**Non-repudiability:** The requirement of non-repudiability is a fundamental property defining the concept of trustless systems benefitting online advertising ecosystem. A node making a transaction should provide proof of identity such as the date the block is created so that its identity is unequivocally linked to the block. The node cannot repudiate the associated transaction to the block. This property can be guaranteed with current blockchain technology.

**Quality information:** The uniqueness of the challenge of online advertising comes from its dependence on quality information. It is not enough to merely consider the transactional benefits, namely authenticity, which can come from the adoption of a blockchain based market model. Examples of quality information include: is the ad viewable; is a human viewing it; and what is the page context where the ad is shown. Quality assessment can take place on three to four different levels; a publisher (a company), a website, a page on a website, an ad impression. There is also the consideration between delivery, for example, if the ad is viewable and if a human sees it, and value, which is concerned with the associated ROI. Whereas delivery is focused on assessing - as a binary statement - whether there is potential for ROI or not, the value is focused on assessing how much potential there is.

The potential value of ad placement and the associated risks are still poorly understood matters and need to be carefully considered in the context of blockchain implementations. The basic premise is that whatever quality information is seen essential is encoded as part of each created block. A problem stems from the fact that in most cases it cannot be themselves who are generating such information. A paradox is created; while blockchain is adopted to avoid the need for third parties, such information would depend on third parties of some sort. It is in itself a complex problem complementary to the blockchain protocol discussed in this document.

**Energy efficiency:** Energy efficiency is not a direct online advertising related requirement. It concerns the whole blockchain technology, hashing, and mining. It must be a requirement for any ICT solution nowadays not to consume excess energy or emit unnecessarily $CO_2$ to burden the environment in any circumstances. Online advertising is not an exception. A comparison should be made between the blockchain solutions and substitutes. Energy usage is one of the many competing optimization factors, unfortunately in many cases overdriven by economics, resiliency, scalability, security or quality. Transparency of energy consumption data of different solutions is low or non-existent. More focus on energy consumption is needed from the researchers and the industry.

### 4.3.3 Analysis of Blockchain Solutions and Platforms

Blockchain technology has an inherent potential to be part of a solution for some of the issues burdening online advertising (ad fraud, brand safety, lack of transparency, and hidden fees). Blockchain technology is replacing subjective human trust with objective mathematical trust and provides a novel method for transactions between organizations, individuals, and machines. Transactions could obtain significant protection against intentional fraud or errors. All parties could trust the immutability of transactions without third-party verifiers.

Blockchains can be programmed to support privacy, secrecy, and transparency simultaneously, which are vital requirements of widely adopted common online advertising systems. Blockchain's potential to reduce ad fraud relies on two theories: 1) the higher the cost the actor has to pay to identify themselves, the less likely malicious and non-intended use is, and 2) the degree to which solving the puzzle (mining) requires computing resources and energy is the degree to which exploiting the system becomes uneconomical.

The basic idea behind some of the blockchain solutions, in the online advertising ecosystem, is presented in Figure 24. Note that the presented idea has not been implemented as such into any of the analyzed blockchain based solutions for online advertising in Publication IV.

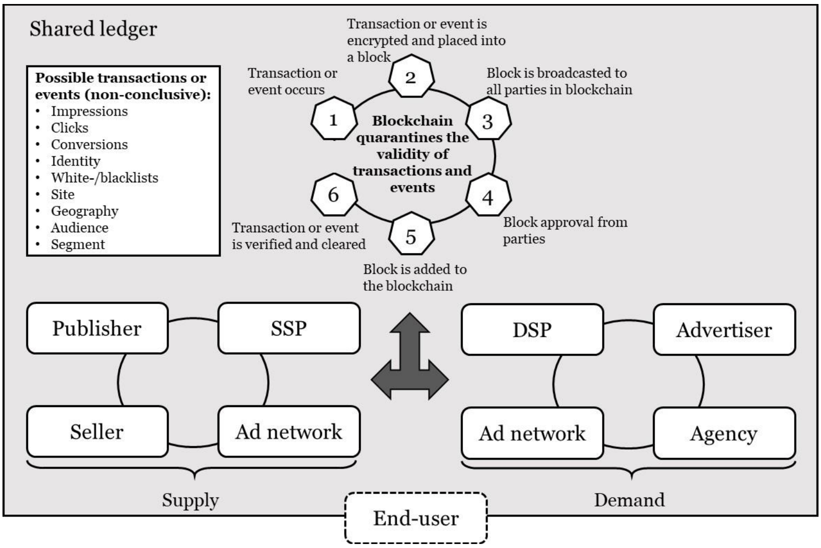


**Figure 24.** The basic idea of blockchain in the online ad ecosystem.

The idea is that all parties share the same essential information (shared ledger) on transactions or events and all parties do approval of each block. Therefore, each transaction or event is transparent.

Blockchain technologies promise to offer solutions to transactional systems. No widely adopted blockchain based application for online advertising has been implemented as of Q1/2019. A thorough literature review and industry analysis were conducted. Several commercial entities have made proposals or actual proof of concept implementations of blockchain in the online advertising context. The following solutions were analyzed: Adchain, AdEx, Comcast blockchain, Basic Attention Token (BAT)/Brave, NYIAX, Madhive, and Papyrus. The following blockchain platforms were also analyzed; Bitcoin, Ethereum, Ripple, Counterparty, Omni, Open Transactions, BitShares, and Colored Coins.

It is justified to say that none of the existing available blockchain based solutions available for online advertising meets the presented five requirements. No solution has even near the features, volumes or market adaption to show evidence which would be convincing. A common standard or dominant design in the context of online advertising has not been formed yet.

Data was gathered from public sources. There are uncertainties in the scalability data, as many of the solutions are in the very early phases of development or market adaptation is low. Three of the solutions were Ethereum based, and therefore inherit the fundamental properties of Ethereum. In respect to the requirements, Adchain and AdEx seem like most promising solutions. Alternatives to existing solutions can come from selecting another blockchain platform.

All the analyzed blockchain platforms had a somewhat different proof method. In addition, all platforms have capabilities to perform transactions and enrich data off-chain. Off-chain processing is needed for scalability but at the cost of losing the authentic security of blockchain. As they are off-chain, they are software, which are interesting targets to exploit. All of the analyzed platforms relied on open source and had a community developing the entire platform or at least parts of it. The best-suited platforms which have the potential to meet the requirements of online advertising were Bitshares and Lightning Network technology, which promises scalability to billions of transactions daily. The fit for online advertising is not 100%, some compromises must be made to the requirements. Another finding is that the platforms relying on pure PoW do not scale to online advertising without a significant part of the application logic off-chain. Once the central part of application logic is off-chain, it contradicts to the initial benefits of the blockchain.

## 4.4 Discussion

A twofold approach was taken to uncover the challenges related to energy consumption of online advertising. On the one hand, the amount of energy consumed and $CO_2e$ produced by online advertising and ad fraud were presented. On the other hand, one potential technology to remove ad fraud related traffic from the network, thus reducing energy consumption globally, was analysed. In the following sections, the results are discussed.

### 4.4.1 Online Advertising Energy Consumption

Growing energy consumption is a global problem. The ICT industry enables substantial energy savings in many industries through automation, for example. Nonetheless, the ICT industry should also reduce its energy consumption and $CO_2e$ emissions. Electricity price is predicted to rise, as it has risen for decades. It will be interesting to observe at which price point the ICT industry becomes more enthusiastic about energy efficiency.

A framework for assessing energy consumption and $CO_2e$ emissions for the EIA of the Internet service was created. Economic and social impact analyses were scoped out from the framework. As a justification of the framework, it was used to assess the energy consumption of online advertising and the results suggest that a substantial portion of HTTP traffic is ad related. Even with uncertainties considered, online advertising consumes vast amounts of energy.

All traffic classes include online advertising to some extent. In the web, email, and data traffic class the amount of online advertising ranges from 25–75% of the traffic, being significantly less in other classes. The impact of the share of online advertising creates the most significant systemic uncertainties, which is not surprising, as it is in the highest level of analysis abstraction on top of the infrastructure, protocols and traffic classes. The results can be repeated quickly and changing any of the input parameters is possible, including the percentage of online advertising for each traffic class. A Python simulation was also created and shared, which allows future researchers to investigate any Internet service by changing the input parameters. The source code of the simulation is available at GitHub [148].

The main factors affecting the output results were 1) share of online advertising in each traffic class 2) uncertainty based on the base value year, and 3) the inclusion of DCs and end devices in the system boundary.

When analyzing the results, it should be taken into account that many of the most widely used Internet services are free, as the business logic is based on advertising, rather than pay-as-you-use. Changing this business model would increase energy efficiency, but at the cost of lower adaptation level for services.

According to a web publication [149], Netflix's share of the total downstream traffic in America is 37.05%. Let's assume this is their global share. If Netflix changed its business model to that of Spotify, which is free to use if the user accepts advertisements, the effect on the Internet energy consumption would be substantial. If an additional 10% is assumed as the advertising video traffic, based on the framework, on a global level additional 42.02 TWh of energy would be consumed, and 23.76 million tons of $CO_2e$ emitted (without taking uncertainties into account).

### 4.4.2 Blockchain as a Solution for Reducing Ad Fraud

One possible question is: If blockchain was a holistic solution for online advertising and ad fraud reduction, what would the solution look like? The answer is far from trivial.

Many blockchain companies are marketing new platforms aiming to decentralize the whole online advertising process [150]–[152]. Promises include removal of intermediaries and linking advertisers and producers without risk. One company utilizes smart contracts and cryptographic keys on a private blockchain to create a data aggregation database for advertisers and producers. Another company uses marketing to introduce a new protocol, based on the private blockchain, promising a solution to ad fraud and lack of trust problems (similar to Figure 24). In all commercially available solutions, blockchain is promised to contain a single source of truth (shared ledger) for critical information. None of the investigated cases in Publication IV provided meaningful evidence to back up these claims. Also, the ad industry is not convinced [153]. Michael Tiffany, a co-founder and a president of White Ops said [153]: "Blockchain, in its current form and use, will have about as much impact on preventing ad fraud as Bitcoin has had on the credit card industry. However, if a blockchain is ultimately used to record unforgeable, non-repudiable attestations about a billable advertising event from multiple parties, then the culpable parties involved in the supply chain could more easily be pinpointed, held accountable and deprived of fraud-driven revenue."

The author’s opinion is that a well-functioning blockchain solution for online advertising that addresses ad fraud in a meaningful way should have the following characteristics: 1) decentralized and autonomous solution, 2) open source, 3) transactions and quality information are on-chain, 4) removes intermediaries and ensures transparent supply-chain, 5) low latency, and 6) is based on PoW consensus.

While some form of a blockchain based approach may indeed prove to be suitable for addressing issues eroding trust in online advertising, multiple important questions require answers before achieving a possible industry-wide implementation. For example, whereas Bitcoin, the best-known implementation of blockchain technology, handles 500k transactions per day, the programmatic advertising ecosystem manages billions of transactions per day [154]. Zheng et al. (2018) conducted a survey study on blockchain challenges and opportunities. The conclusion was that there exists scientific interest to find solutions to problems burdening blockchain technologies [155]. According to Bano et al. [156], current research on blockchain scalability focuses on solutions to improve performance while maintaining the decentralized nature of blockchain. Some of the technologies being researched include multiple blocks per leader, collective leaders, parallel blockchain extension, and sharding transactions [156]. One concrete example of parallel blockchain extension research is the Canopus technology, which utilizes DC network topology, consensus semantics, and parallelism. Canopus could have the potential to achieve consensus scalability capable of processing million transactions per second [157]. In addition to interest from academic researchers, blockchain has caught the interest of major industry players like Microsoft Azure [158], Amazon AWS [159], and IBM [160]. There is a strong case to support a gradual increase of blockchain adoption as part of a broader effort to increase transparency in the advertising ecosystem.

The answer to the question at the beginning of this section is: Ad fraud is a complex and poorly understood problem. There are too many open questions to propose a detailed suitable approach.

# 5. Conclusions

There are two ways to lower the environmental impact of ICT. The first way is to improve the energy efficiency of ICT. One practical solution is utilizing waste heat from data centers (DCs) to district heating (DH). Waste heat utilization has benefits for both DC and DH operators, and it is a viable solution environmentally, economically, and socially. The second way is making ICT services consume less resources and energy. One practical solution is reducing ad fraud traffic in online advertising and thus the impact of the overall ICT resource consumption. The impact of online advertising and ad fraud on the environment is significant and therefore reducing ad related traffic can have positive implications on ICT energy consumption

Awareness of energy-related costs must reach decision-makers in the ICT industry. The reasons for this are not only cost savings and higher profits but also the contribution to energy consumption and $CO_2$ emission reduction.

The Internet consumes vast amounts of energy and creates $CO_2e$ emissions of global significance. The exact figures were challenging to calculate due to the enormous complexity of the Internet. The results from utilizing the framework introduced in Publication III is enough to conclude that improving the energy efficiency of the Internet is a relevant matter. By utilizing the framework, the aim was to identify the part of energy consumption related to online advertising, and the amount of energy consumed by ad fraud. The impact of ad fraud reduction will not manifest immediately, but somewhat gradually. While the impact of invalid online advertising significantly affects the advertising economy in monetary terms, it also consumes lots of energy and has a hefty carbon footprint.

With the current trend, the $CO_2e$ emissions will continue to grow over time in many industries. It is essential that industries leveraging Internet technologies take the necessary steps to stop this trend and to ultimately decrease the $CO_2e$ emissions as early as possible. Awareness of the problem is the first step towards more concrete actions.

As a potential solution to the ad fraud problem, a review on existing blockchain platforms and blockchain based solutions addressing online advertising was conducted. Based on the requirements of the online advertising industry, the conclusion was that none of the solutions evaluated presented evidence to fulfill the requirements.

In future research, different pricing structures and their effects on waste heat utilization business cases should be analyzed, e.g., fixed pricing and hourly pricing. Furthermore, the effects of different pricing structures should be analyzed to see how they affect investments in DCs. Researchers could also investigate how the following aspects change the NPV model output: 1) the use of on-site renewable energy sources for priming, 2) the effect of using an uninterruptible power supply (UPS) as a source of electricity, 3) the effect of waste heat reuse on the cash flow of a DC operator in the business case of transforming workloads into public cloud, and 4) the content of the bilateral commercial agreements between DC and DH operators.

An inventory-based bottom-up analysis of all technology domains should be investigated. Such an analysis would increase the accuracy of environmental impact assessment results and remove uncertainties as much as possible. The same applies to traffic classes. The role of software in energy efficiency improvement initiatives should also be investigated further. There are reference models for greener software [29]. They are not widely applied. In addition, the trend towards smartphones, smart TVs and clouds, shift computing and storage to service provider DCs, therefore potentially decreasing energy consumption through scale and resource utilization rate improvement. None of the energy consumption improvements happen by accident; instead, they are a result of systematic energy efficiency improvement initiatives at all levels of the ICT industry.

Finally, more research is needed to understand the financial aspect of online advertising and how it relates to blockchain; under which conditions will advertisers and their agency representatives consider significant investments in the token economy. The focus should at least initially be more on the technical challenges, and less on the financial transaction aspect.

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According to the IPCC report in 2018, the current rate results in likely global warming of 1.5 °C between 2030 and 2052. Despite the positive impacts of dematerialization, decarbonization, and demobilization, there is a growing concern on the environmental impact of ICT. Can services moving online be considered sustainable development? There is a possible rebound effect; even though the energy efficiency of devices has improved, the scale of use has increased at a rate which results in an increase in the total energy consumption.

There are two ways to reduce ICT energy consumption: 1) improve the energy efficiency of the devices and 2) make ICT services consume less resources and energy. This thesis assesses the energy consumption of the ICT infrastructure and gives case examples of both options of consumption reduction. The first case examines reusing of waste heat emerging from data centers, and the second case focuses on reducing ad fraud traffic in online advertising.

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