# Bitcoin Mining in Sweden

## – Prospects for implementing Bitcoin mining operations in the Swedish energy system

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Examensarbete 2022
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Sammandrag

Bitcoin mining är en industri som i flera år har kritiserats för sin elkonsumtion, som globalt idag motsvarar elkonsumtionen hos små länder som Sverige, och det tillhörande klimatavtrycket. Elkonsumtion är dock inte alltid likställt med växthusgasutsläpp och få studier har gjorts kring ämnet med fokus på Sverige. Detta är bakgrunden till arbetets genomförande som ämnar att bidra med nya rön till det annars inte särskilt transparenta området Bitcoin mining.

Studien har undersökt effekten som svensk Bitcoin mining verksamhet har på det svenska energisystemet i termer av elkonsumtion och växthusgasutsläpp, med fokus på el och värme. Studien har delvis genomförts i syfte som ett svar på det föreslagna förbudet mot Bitcoin mining verksamhet i Sverige och Europeiska unionen som lades fram av generaldirektörerna för Finansinspektionen och Naturvårdsverket hösten 2021.

Data på Bitcoin mining industrins omfattning är generellt otillgänglig och ofta fylld med nyanser och olika perspektiv beroende på antaganden kring emissionsfaktorer, teknologi och tidseffekter. Datainsamling har i studien kombinerats med beräkningar och scenarioanalys för att undersöka effekterna av värmeåtervinning från Bitcoin mining maskinerna, elanvändning samt utnyttjandet av överskottsproduktion av el. Genom de olika fallstudierna kan det fastslås att den svenska Bitcoin mining verksamhetens växthusgasutsläpp motsvarar ett avrundningsfel på de totala utsläppen i ett intervall från en promilles ökningen till en halv procents minskning av Sveriges totala växthusgasutsläpp beroende på de olika fallen.

Studien föreslår att istället för att förbjuda Bitcoin mining verksamhet i Sverige och i den Europeiska unionen borde reglering och styrmedel användas för att skapa ekonomiska incitament som gynnar klimatsmart Bitcoin mining verksamhet. Detta genom att exempelvis uppmuntra användningen av överskottsel samt återvinning av restvärmen, exempelvis via fjärrvärmesystemet. Vidare hittar studien ett potentiellt användningsområde för Bitcoin mining som ett substitut till traditionell elvärme under specifika tekniska antaganden

Nyckelord

ASIC, Bitcoin, Bitcoin mining, proof-of-work, blockkedja, fjärrvärme, värmeåtervinning, klimatförändring, Sverige

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Abstract

Bitcoin mining is an industry which for many years has been criticized for its electricity consumption, which globally today equals roughly that of small countries such as Sweden, and its subsequent contribution to climate change. However, electricity consumption does not by default equals greenhouse gas (GHG) emissions and not many studies have been done on the subject with a focus on Sweden, hence this study aims to provide some clarity to the otherwise opaque space of Bitcoin mining.

The study has been examining the effect Bitcoin mining operations have on the Swedish energy system, in terms of additional power consumption and GHG emissions, with a focus on electricity and heating. The study has partly been conducted as a response to the proposed ban of Bitcoin mining in Sweden and the European Union by the Director Generals at the Swedish Environmental Protection Agency and the Swedish Financial Supervisory Authority in the fall of 2021.

Data covering the Bitcoin mining space is in general opaque in terms of data availability and filled with nuances and perspectives depending on assumptions, hence multiple cases have been used to account for different carbon intensities, technologies, and time effects. Data sourcing has been combined with calculations and scenario analysis. The study is including an examination of the effects of heat recovery from the Bitcoin mining machines as well as power consumption and potential use of future excess electricity. Through the different cases it is observed that the effect Bitcoin mining has on the overall GHG emissions of Sweden corresponds to a rounding error, ranging in an interval of an increase of national GHG emissions by a tenth of a percent to a reduction of national GHG emissions of around half a percent depending on the different cases.

The study suggests that instead of banning Bitcoin mining operations within Sweden and the European Union, regulators should use administrative tools and economic incentives to encourage Bitcoin miners to use renewable energy and excess electricity. It is also reasonable to incentivize Bitcoin mining operations to make use of the generated waste heat, which could potentially be used in the heating of individual homes or in large scale district heating facilities. The study also finds a potential use case for Bitcoin mining machines as a future substitute to electric heaters under certain technical conditions.

Keywords

ASIC, Bitcoin, Bitcoin mining, proof-of-work, blockchain, district heating, heat recovery, climate change, Sweden

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# Foreword

This analysis has been carried out in the form of a master's thesis for the Division of Environmental and Energy Systems Studies at Lund University, Faculty of Engineering (LTH) with assistance from Arcane Crypto. The master's thesis constitutes the last step of the Master of Science in Engineering, Environmental Engineering, program at Lund University, Faculty of Engineering (LTH) and was carried out during the spring semester of 2022.

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Lennart Söder (KTH)

Marcus Thern (LTH)

*Sixten Hager*

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# Glossary

**3GDH:** Third generation district heating.

**4GDH:** Fourth generation district heating.

**ASIC:** Application-specific integrated circuit.

**Bitcoin:** Refers to the Bitcoin network, including the Bitcoin protocol and its inherent properties.

**Bitcoin protocol:** The protocol that defines the rules of the Bitcoin network and the cryptocurrency.

**bitcoin:** The unit of account and the native cryptocurrency of the Bitcoin network.

**Bitcoin miner:** An entity using computational machines such as ASICs to mine bitcoin.

**Bitcoin mining:** The computational process which secures the Bitcoin network.

**CFM:** Cubic feet per minute.

**$CO_2$-eq:** Carbon dioxide equivalents.

**COP:** Coefficient of performance.

**Cryptocurrency:** A decentralized digital currency that is minted through cryptographic means and operates using distributed ledger technology.

**GHG emissions:** Greenhouse gas emissions.

**Distributed ledger technology:** Any type of consensus-oriented distributed database that records information on a shared ledger.

**Decentralization:** The process of dispersing power or control away from a central point or entity.

**Ledger:** A computer file which stores records, e.g. documentation of transactions.

# Contents

# 1

# Introduction

In November 2021, the Director General at the Swedish Environmental Protection Agency (Naturvårdsverket), Björn Risinger, published together with the Director General at the Swedish Financial Supervisory Authority (Finansinspektionen), Erik Thedéen, an article calling for a complete ban on Bitcoin mining. Not only in Sweden, but in the European Union. The reason stated was the high energy consumption associated with the proof-of-work technology which underlies Bitcoin mining, the computational process securing the Bitcoin protocol and subsequently the Bitcoin network (Bitcoin Project, 2022). Something, they explain, is not reasonable if we want to mitigate climate change (IPCC, 2022) and reach the targets of the Paris Agreement, both nationally and globally (Dagens Nyheter, 2021).

Energy consumption however, or more specifically electricity consumption, is not always equivalent to greenhouse gas (GHG) emissions. Bitcoin miners operate in a fast moving global competitive landscape in which only the cheapest electricity is consumed. Today, the cheapest available electricity is generally excess electricity, due to overproduction, distribution issues and grid inefficiencies, or electricity generated from renewable energy sources (International Renewable Energy Agency, 2021). A perspective that was pointed out as a response to the article by the Head of Physical Power Management, Henrik Juhlin, at the Swedish state-owned power company Vattenfall. Juhlin explains that Bitcoin mining instead could be viewed as a tool for balancing the load on the electricity grid when the power supply fluctuates, a common property in countries like Sweden which rely on renewable energy sources like wind and hydro power for a significant portion of its electricity generation (The Swedish Energy Agency, 2022). Juhlin continued explaining that banning Bitcoin mining in the European Union could, on the contrary, increase global GHG emissions if mining instead would take place in countries more reliant on coal and other fossil fuels for their electricity generation (Sveriges Television, 2021).

In accordance with Juhlin, the Bitcoin Clean Energy Initiative released a short research paper in April 2021, explaining how the unique properties of Bitcoin miners as electricity buyers of last resort could, with proper integration, work as an ideal complement for electricity generation and storage, increasing profitability and stability for the expansion and build-out of renewable energy sources globally (Bitcoin Clean Energy Initiative, 2021). However, this reasoning and line of thought has been criticized. A report from 2019 explains that even though Bitcoin miners may be able to take advantage of temporary excess electricity from renewable energy generation, they will increase the base load demand on the electricity grid throughout the year. A base load which in some cases may not be renewable (de Vries, 2019).

In terms of what energy that is used to power the Bitcoin network, the data is generally uncertain and opaque with many different estimations available. For example, it is estimated in a report from 2019 that the share of renewable energy used in Bitcoin mining amounted to 73%, while the remaining 27% consisted of fossil fuels and nuclear energy (CoinShares, 2019). Another report released in 2020 estimated the renewable energy share to 39% (Cambridge Center for Alternative Finance, 2020), and yet another from 2021 to 56% (Bitcoin Mining Council, 2021). To put these estimations in perspective, the average renewable energy share in the European Union was 22.1% in 2020 (Eurostat, 2022).

Apart from the data uncertainties in the sector and the great variance in estimations, one major obstacle in the discussion surrounding the Bitcoin energy consumption is the question of what underlying use case Bitcoin has. The argumentation and course of reasoning changes heavily depending on what societal value is ascribed to the Bitcoin network by the observer. If the Bitcoin network is assumed to have no utility whatsoever, it could reasonably be argued that all energy spent on securing the protocol is wasted and that mining should be heavily regulated. This in order to use energy and resources more wisely on a societal level. On the other hand, if the value of Bitcoin is assumed to be more than non-existent, the nature of the discussion changes. Focus is shifted beyond Bitcoin mining's "be or not be" and questions regarding how to effectively implement Bitcoin mining in society becomes more interesting. From this viewpoint it could even be argued that Bitcoin mining should be promoted in society from an environmental, economical, and humanitarian standpoint. It then also becomes relevant to compare the energy use of Bitcoin with other energy demanding industries and compare their societal values. Further, it also becomes interesting to explore what broader implications an open and global monetary system such as Bitcoin could offer the world on a social level. This was partly done in an article by Lundgren and Rosenbaum, also as a reply to the article by Risinger and Thedéen, where they claimed that the move towards a deflationary money system (such as Bitcoin), with an appreciating currency instead of a depreciating one which is the case in an inflationary money system, could alter the current incentive structures, consumption patterns, and the societal values which have caused a large portion of the climate related problems observed today (Lundgren Rosenbaum, 2021). This perspectives was further explained in an article published on World Economic Forum in 2022, where an argumentation was made that the debate surrounding the energy use of Bitcoin is highly westernized, and that the economic freedom which is provided through Bitcoin to anyone with an internet connection is often ignored (Cheikosman, 2022).

The discussion surrounding the Bitcoin energy usage is not only restricted to Sweden and the European Union. In June 2021, China banned all Bitcoin mining operations within their borders as it was seen as an obstacle for reaching carbon neutrality since a large portion of the Bitcoin mining operations in China have historically been reliant on coal and other fossil fuels (Fortune, 2021). Another actor which has taken a strong position on Bitcoin and Bitcoin mining is the American car manufacturer Tesla. Tesla announced in February 2021 that they had added bitcoin (note that *bitcoin* refers to the unit of account and the native cryptocurrency of the Bitcoin network, while *Bitcoin* refers to the Bitcoin network, including the Bitcoin protocol and its inherent properties) to their corporate treasury with the aim to adopt it as a means of payment for their products and services. This stance however shifted rapidly with the growing energy and subsequent environmental concerns for Bitcoin, and Tesla has since stated that they will not start using bitcoin as a payment option before it gets less fossil dependent (BBC, 2021).

## 1.1 Scope

The discussion of what value an open and decentralized monetary system outside of state control, such as Bitcoin, has for the individual and the society is both grand and complex and lies outside the scope of this study. However, these different perspectives are nonetheless important for the reader to keep in mind throughout the study to fully comprehend all the nuances of the results.

The study aims to explore the potential integration of Bitcoin mining in the current and future energy system of Sweden. This in order to provide some clarity to the debate around the energy consumption and the carbon footprint in terms of GHG emissions of the Bitcoin network. Focusing on the electricity consumption and the waste heat generation associated with ASICs (application-specific integrated circuits), the computation machines used for Bitcoin mining, the study aims to answer the following questions:

- **What is the climate impact of integrating Bitcoin mining in the Swedish energy system?**
- **What are the prospects for utilizing waste heat generated by Bitcoin miners in the Swedish energy system?**
- **What are the prospects for using excess electricity generated in Sweden for Bitcoin mining?**

## 1.2 Outline

### Section 1

Section 1 provides an introduction of the underlying problem and discussion surrounding the Bitcoin energy consumption and carbon footprint. The scope and the problem statements of the study are presented.

### Section 2

Section 2 gives a high level description of Bitcoin, the underlying blockchain technology, the Bitcoin mining process as well as its relation to electricity consumption. A non-technical explanation of the proof-of-work consensus mechanism, ASICs, and hash rate are also presented.

### Section 3

In Section 3, the methodology is presented with an associated description and brief discussion of the data sources and the literature.

### Section 4

Section 4 gives a brief background on the Swedish energy system, including electricity generation, district heating, and carbon intensity.

### Section 5

In Section 5, the extent of Bitcoin mining operations located in Sweden is analyzed.

### Section 6

Section 6 examines the prospects for utilizing waste heat generated by Bitcoin miners located in Sweden.

### Section 7

In Section 7, the climate impact is calculated, focusing on different scenarios and cases presented in the previous sections.

### Section 8

Section 8 displays a summary and an analysis of the results.

### Section 9

In Section 9, the results and the associated findings of the study are discussed.

### Section 10

The conclusions of the study are presented in Section 10.

### Section 11

Potential future research topics are discussed in Section 11.

### Section 12

Bibliography and references.

# 2

# Background

## 2.1 Bitcoin

In October 2008, an anonymous entity named Satoshi Nakamoto sent a link leading to a research paper with the title: "Bitcoin: A Peer-to-Peer Electronic Cash System" to a mailing list consisting of cryptography enthusiasts from all around the world (Finley, 2018). The paper outlined in detail how to implement a secure and trust-less system for electronic transactions without relying on a third party (Nakamoto, 2008). A third party, "a person other than the principals", for example referring to a bank, a law firm or a government acting as a middleman in order to remove counterparty risk between actors making a transaction of value (Merriam-Webster, 2022). On January 3rd 2009 the first transaction based on these principles took place and Bitcoin was born (Redman, 2020). 13 years and almost a billion processed transactions later (Nasdaq, 2022), Bitcoin has grown into a global network, reaching a market capitalization of around half a trillion dollars (Blockchain.com, 2022), making it one of the top 20 largest global currencies with regards to market capitalization (Coinmarketcap, 2022). It is estimated that approximately 114 million people own bitcoin (Wall Street Journal, 2021) and in September 2021 the Latin American country El Salvador was the first nation to adopt bitcoin as legal tender, giving it global currency status (BBC, 2021).

It is believed that the creation of Bitcoin was a response to the global financial crisis of 2008 and the perceived failure of the financial system and the mismanagement of corporations, governments, and institutions all around the world, most notably in the United States of America (Noogin, 2018). Bitcoin is often viewed as an open and free monetary network, which in simple terms means that participation in the network allows for direct transactions between parties in a censorship resistant way with direct clearing and ownership. Similar to the properties of transacting in paper bills or coins, but in the digital realm. This idea and the removal of third parties allows for an alternative financial system, independent of central banks, governments, and traditional banking (Jenssen, 2014). The fact that Bitcoin is an open, permission-less, and censorship resistant network, allows anyone with an internet connection to participate. This has been a subject for critics who claim that Bitcoin provides international payment rails for terrorism, money laundering, and capital flight (Dion-Schwarz et. al., 2019). Advocates on the other hand claim that Bitcoin should be viewed as a pro-democratic and humanitarian invention which allows people under currency systems with run-away inflation to protect their wealth, finance activism, or escape from countries with non-democratic and authoritarian regimes. Notable on this subject is the work by Alex Gladstein from the Human Rights Foundation, regarding the connections between colonial history, money control, and Bitcoin (Gladstein, 2021).

A recent example illustrating the complexity surrounding Bitcoin is the current conflict between Ukraine and Russia. Concern has been expressed regarding Russia avoiding economic sanctions through Bitcoin and other cryptocurrencies, for example through the sale of natural gas and other resources with bitcoin as payment, as well as Russian oligarchs protecting their assets (BBC, 2022). Attention has also been lifted towards people, both in Russia and Ukraine, who have escaped their respective countries with their wealth intact outside the control of the Ukrainian and Russian government through Bitcoin. Further, Ukraine has received around $100 million in cryptocurrency donations for financing their military. The Ukraine-Russia conflict illustrates the dilemma and the double nature of a global, digital, open, and decentralized monetary system outside state control such as Bitcoin (Vox, 2022).

## 2.2 Blockchain technology

The removal of third parties require another method for verifying, securing, and clearing transactions than the ones offered by traditional banking and international trading systems of today such as Fedwire used in the United States of America (Federal Reserve, 2021) or RIX used in Sweden (Sveriges Riksbank, 2021). The technology underlying Bitcoin which is allowing participants to be non-reliant on middlemen, is blockchain technology. Blockchain technology and blockchains are a type of database structure which can be used to store all types of information in a decentralized manner across network participants. In the case of Bitcoin, the blocks in the blockchain store solely information on transactions and balance. The stored data, or the ledger, is often immutable and the blocks making up the blockchain are chained together chronologically after each other. The last block in the chain is the most recent one added and each new block has a cryptographic relationship to the previous one which links them all together in a chain, a blockchain (IBM, 2022). Blocks can be added to the blockchain in different ways. For Bitcoin the method used is proof-of-work, but other methods such as proof-of-stake, proof-of-space, and proof-of-elapsed time are also used in other blockchains (Blockchain Council, 2022).

## 2.3 Bitcoin mining

Bitcoin miners are computers distributed all over the world competing to add the next block in the Bitcoin blockchain. Miners fill their blocks with unconfirmed transactions and start to compete solving a cryptographic puzzle (the hash function SHA-256), a guessing game where the first miner to solve the puzzle is allowed to add their newly created block to the blockchain. When the block is added to the blockchain, the transactions contained in the block are converted from unconfirmed to confirmed. When a new valid block is added by a miner, all miners immediately start to solve for the next block. The miner who solved the puzzle for the most recent block added receives a block reward and the fees associated with the contained transactions. The block reward constitutes the Bitcoin inflation which decreases with 50% for every 210 000 blocks until all 21 000 000 bitcoins have been mined (as compared to the roughly 19 000 000 in existence today). In order to keep the creation of new bitcoin stable and independent of the number of Bitcoin miners solving for the next block, the difficulty of the puzzle to be solved is adjusted every 2 016 blocks so that the time between new blocks stays around 10 minutes. Bitcoin mining is often done through pooling, where Bitcoin miners cooperate and aggregate their computational power into pools and collect block rewards together, sharing the income, making the business model more predictable and income stream more stable (Investopedia, 2022).

## 2.4 Proof-of-work

In addition to confirming transactions and adding new blocks to the blockchain and new bitcoins into circulation, another important role of Bitcoin miners is to secure the network. All this is done through the proof-of-work technology. Proof-of-work forces the participant to prove that some computational power, electricity, has been spent and constitutes the basis for consensus in the permission-less decentralized network (Jakobsson and Jules, 1999). The point of the proof-of-work mechanism is to make it economically expensive to attack the system. The combined computational power of all Bitcoin miners which are competing for solving the next block and adding it to the blockchain is protecting the network. Hence, the only way of breaking the blockchain is by having a majority ($> 50\%$) of the computational power in the solving of the next block. This would make it possible to render transactions and even create new bitcoins outside the consensus of the protocol. An attack on a large network such as Bitcoin, would through this incentive model be extremely costly due to the hardware and electricity investments required. Further, attacking the Bitcoin network has an extremely large alternative cost since the same hardware and electricity used to attack the network could be used to mine bitcoin and generate income for the actor (Investopedia, 2022).

## 2.5 ASIC

In the infancy of Bitcoin, the mining computations could be performed on a CPU (central processing unit) found on a personal computer. However, the competitiveness of the Bitcoin mining space and the subsequently larger computational requirements, have pushed innovation towards building specific Bitcoin mining processors know as ASICs (application-specific integrated circuits). These are computational machines specifically designed and optimized for mining bitcoin and solve the SHA-256, the hash function and the mining algorithm of the Bitcoin protocol. Today, nearly all mining is done through different varieties of ASICs (Coinmarketcap, 2022).

## 2.6 Hash rate

Hash rate, hash power or hash per second, is a measurement of the processing power used to mine cryptocurrencies using proof-of-work. In the case of Bitcoin, each hash rate unit represents the number of double SHA-256 computations performed per second. For example, a network hash rate of 10 TH/s represents 10 trillion calculations per second. Hash rate can be used as a proxy for understanding the amount of computational power trying to verify transactions and add new blocks to the Bitcoin blockchain, and subsequently securing the network (Bitcoin Project, 2022). The Bitcoin network has a hash rate of around 200 million TH/s, or 200 EH/s, as of March 2022 (Blockchain.com, 2022).

## 2.7 Perspectives on energy use

Bitcoin mining, hash rate, and electricity use are correlated with the underlying price of bitcoin since a higher price makes it more profitable to mine. On a general basis, the Bitcoin network will consume the amount of electricity the market is offering in return for the value of the income stream generated by the block reward and the transaction fees. Hence, it is the value of this income stream, which constitutes of the price of bitcoin and the activity of the network as well as the cost and the availability of electricity, which ultimately determines how much electricity is consumed by the Bitcoin network (CoinShares, 2022).

According to the Cambridge Bitcoin Electricity Consumption Index, Bitcoin is estimated to consume approximately 142 TWh per annum globally as of March 2022 (Cambridge Center for Alternative Finance, 2022c). This can be compared to the total annual electricity use in Sweden, which in 2021 amounted to 139.9 TWh (Swedish Energy Agency, 2022), or a share of the total annual global electricity use of 0.62% (International Energy Agency, 2021). Another relevant comparison is with gold and gold mining, which is often considered as a commodity which fulfills a similar societal and monetary function as Bitcoin. Gold and gold mining is estimated to consume 131 TWh per annum. Comparisons with other energy intensive industries are displayed in Figure 2.1 (Cambridge Center for Alternative Finance, 2022b).


*Figure 2.1: Bitcoin energy consumption (BTC) compared to other industrial processes as of March 2022. Comparisons are made on a global scale, if not indicated otherwise, in terms of annual energy consumption (Cambridge Center for Alternative Finance, 2022b).*

The history shows many attempts in predicting the future power consumption of Bitcoin. One example is an article published on World Economic Forum in 2017 which estimated that in 2020 the Bitcoin electricity consumption would equal the electricity consumption of the entire world, based on the historic growth rate of Bitcoin mining (Jezard, 2017). This example illustrates the difficulty in predicting the future Bitcoin power consumption since it is ultimately derived from the underlying price of bitcoin as well as electricity availability and cost (CoinShares, 2022).

# 3

# Methodology

## 3.1 Overview

The methodology consists of a literature study and data collection combined with calculations and case analysis. The study is solely focusing on Bitcoin mining and its integration with the Swedish energy system. Hence, the study is exclusively looking at Sweden. In terms of time frame, the study examines current Bitcoin mining operations in Sweden as a snapshot of the present situation. However, different cases are constructed in order to account for time effects such as technological development and uncertainties in the data. Further, the study is solely focusing on the use-stage of Bitcoin mining, meaning no account is taken to the manufacturing of hardware and other components, transportation, sourcing of raw materials, and other factors which could have an effect on the results. The climate impact analysis is only examining the effects related to climate change in terms of GHG emissions or carbon dioxide equivalents ($CO_2$-eq) emissions. The analysis is done in a step wise manner as seen under Section 3.2 with data and literature sourced as according to Section 3.3.

## 3.2 Analysis

### Step 1

In the first step, the extent of Bitcoin mining operations located in Sweden in terms of power consumption is determined by triangulating estimated hash rate generated within the country and estimated national power consumption ascribed to Bitcoin mining. The data covering hash rate (TH/s) is calculated and transformed into electricity consumption (TWh) and heat generation (TWh and J). Since mining is done with different types of ASICs, which vary highly in efficiency in terms of energy consumption per hash rate (J/TH), and due to the lack and uncertainty in data, different cases are used in the estimation of the national power consumption. Three cases are modelled:

- One base case using the weighted average network efficiency. This constitutes the base case which is used as a reference throughout the study.
- One worst case using data from one of the least efficient machines operating today.
- One best case using data from one of the most efficient machines operating today, considered as a proxy for best available technology.

Step 1 is done through a literature study, data collection, and calculations. The results are used throughout the rest of the study.

### Step 2

In the second step, the prospects for implementing Bitcoin mining in the Swedish energy system is explored. This is one of the core steps of the study and is being done in the form of a technical feasibility study using data and calculations. Possible waste heat recovery methods are assessed based on the scale of Bitcoin mining operations. The study focuses on a large scale case covering waste heat recovery via district heating. Both third (3GDH) and fourth (4GDH) generational district heating systems are assessed in order to account for time effects covering technological development. The results from Step 2 are essential for Step 3 which is the last step of the analysis.

### Step 3

The third step covers an analysis and estimation of the climate impacts associated with the different cases presented in all the previous steps, including different cases for national electricity consumption, heat recovery methods, and other assumptions. Data covering the Swedish energy system including electricity generation and district heating is also taken into account in Step 3. For the electricity used by Bitcoin miners, two different carbon intensities for Bitcoin mining are used to provide further nuance to the analysis in the carbon footprint estimation. One carbon intensity assuming the Swedish energy mix and one assuming an estimation which considers the economic dynamics of the Bitcoin mining industry. The analysis and the subsequent comparison between cases include comprehensive emission metrics such as GHG emissions ($CO_2$-eq) and power consumption (TWh). Step 3 is also including a qualitative analysis covering the potential use of current and future excess electricity. After Step 3, the final results are obtained which are required in order to answer the questions within the scope of the study as stated in Section 1.1.

## 3.3 Data and literature

Data and literature are collected from a variety of sources, including state-owned enterprises, public companies, universities, governments, and independent reports. The majority of the data is sourced from 2021, while older data is generally not older than three years. Some analysis is provided below with regards to the quality of the data in terms of completeness, time, and technology, but a more comprehensive discussion covering the general uncertainties, system boundaries, and assumptions is provided in Section 9.1.

### Swedish electricity generation

Since the study is examining the current Bitcoin mining situation in Sweden, data from 2021 is used since no complete data for 2022 is yet available. Even though a time frame covering multiple years would provide a more realistic description of the Swedish electricity generation with its subsequent variations and long term trends, only data from 2021 is used. This since data from 2020 most likely will distort a multi year time frame as national electricity generation was effected by the global lockdowns as a consequence of the recent COVID-19 pandemic.

Svenska Kraftnät is a state-owned enterprise in charge of monitoring, improving, and balancing the Swedish electricity grid, as well as having oversight of electricity trading within the Nordics and the European Union (Svenska Kraftnät, 2022). Reports and subsequent data from Svenska Kraftnät has been used for current and estimated future electricity generation and distribution.

Data covering the carbon intensity of the Swedish electricity generation has been collected from the open-source visualization tool provided by electricityMap, which in turn is partly based on data provided by Svenska Kraftnät. The carbon intensity of the Swedish energy mix from which electricity is generated has been estimated using the mean value of the hourly carbon intensity for 2021 (electricityMap, 2022).

### Swedish district heating

Literature covering the Swedish district heating system is provided by multiple sources, including non-profit organisations such as Swedenergy, government agencies such as Statistics Sweden, state-owned enterprises such as Vattenfall, and various academic studies on the topic. The data used has a similar time frame to that of the electricity generation and includes energy sources, heat generation, and carbon intensity.

### Bitcoin power consumption, hash rate, and ASIC data

For Bitcoin mining data, the two major sources are Cambridge Center for Alternative Finance (CCAF) and CoinShares. The data is sourced from 2021 and 2022. CCAF has a top-down approach for estimating hash rate and power consumption for individual countries. Using data from mining pools in order to estimate the geographic distribution of miners, combined with energy efficiencies and carbon intensities for the countries, both hash rate and electricity consumption are estimated. The data covers around 35% of global total hash rate. Further, the use of virtual private networks (VPN) can have an altering effect on the data (Cambridge Centre for Alternative Finance, 2022).

Contrary to CCAF, CoinShares is using a bottom-up approach by identifying all mining facilities in each country, which is then triangulated with data from CCAF and other available sources to estimate the Bitcoin electricity consumption and subsequent carbon intensity for each country (CoinShares, 2022).

Total hash rate for the Bitcoin mining network has been sourced from the company Blockchain.com. Daily hash rate for 2021 has been used to estimate an annual mean (Blockchain, 2022).

Product specifications covering the different ASIC machines are collected from the ASIC Miner Value website.

### Other data

Data such as COP factor, heat exchanger efficiency, and district heating temperature requirements have been sourced from literature or from people within the academic profession covering the relevant topic.

# 4

# The Swedish Energy System

In order to understand the relative extent of Bitcoin mining operations in Sweden, how Bitcoin mining can be implemented in the Swedish energy system, and what the subsequent climate impact is, the Swedish energy system is examined with a focus on electricity generation and district heating. Values presented throughout this section are used in the upcoming sections if not indicated otherwise.

## 4.1 Electricity generation

Sweden has one of the most sustainable power production systems in the world. According to the Swedish Energy Agency, total electricity generation reached 165.5 TWh in 2021. The majority of which being generated by hydro and nuclear power (Figure 4.1). In terms of supply and demand, Sweden is a net exporter of electricity with 25.6 TWh being exported in 2021, mainly to the Nordic neighbouring countries and mainland Europe. The domestic electricity use amounted to 139.9 TWh in 2021 (The Swedish Energy Agency, 2022) and the total installed capacity amounted to approximately 41 200 MW as of January 1st 2021 (Svenska Kraftnät, 2021).

Climate impact associated with the Swedish electricity generation in terms of $CO_2$-eq emissions inhibit some nuances dependent on assumptions and data choices. For 2021, the Swedish energy mix is estimated to have generated **37.9 g of $CO_2$-eq per kWh** (electricityMap, 2022). This is the value which is used later on in the study in accordance with the geographical focus of Sweden. However, when including imports and exports of electricity, the number reaches 45.5 g of $CO_2$-eq per kWh which can be explained by the relative higher carbon intensity of the surrounding neighbouring countries and subsequent electricity trading partners of Sweden.

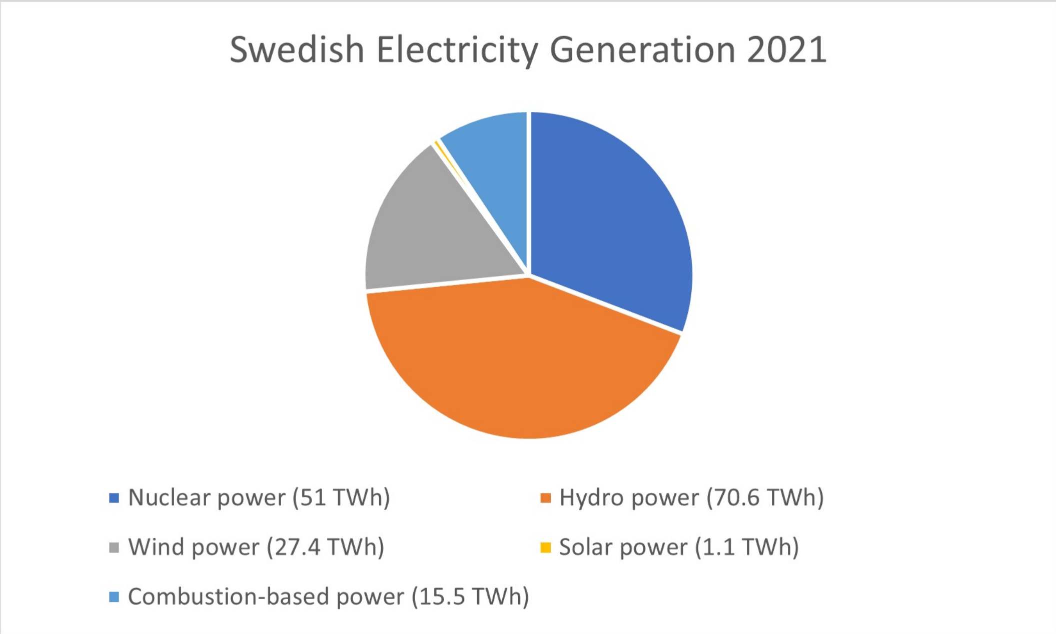


*Figure 4.1: Energy source composition of the Swedish electricity generation 2021 (The Swedish Energy Agency, 2022).*

### 4.1.1 Distribution

In 2011, Sweden was divided into four areas for production, consumption, and trading of electricity in order to stimulate and incentivize local electricity generation as well as letting market forces signal where extended transmission and distribution capacity are needed. The areas are called electric areas and are; SE1 (Luleå), SE2 (Sundsvall), SE3 (Stockholm), and SE4 (Malmö) as seen in Figure 4.2 (The Swedish Energy Markets Inspectorate, 2022).

Sweden is a large country with a disproportionate distribution of consumption and production of electricity, meaning large variations can be observed between different electric areas. The differences in installed capacity, electricity consumption, availability of renewable energy, as well as transmission capacity per electric area have resulted in a tendency towards cheaper and more renewable electricity in the north as seen in Table 4.1. These insights are valuable when considering the location and carbon intensity of Swedish Bitcoin mining operations later on in the study.

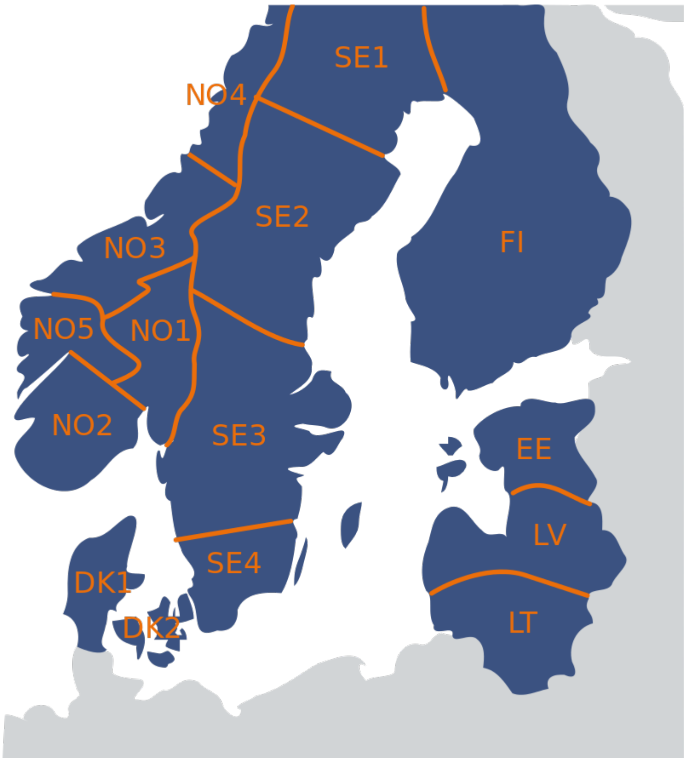


*Figure 4.2: Electric areas of Sweden (Wikipedia user Hour710).*

*Table 4.1: Installed capacity, transmission capacity, average electricity price, and share of renewable energy of installed capacity per electric area as of January 1st 2021 (Svenska Kraftnät, 2021; The Swedish Consumer Energy Markets Bureau, 2022).*

| **Area** | **Installed capacity** | **Transmission capacity** | **Price** | **Renewables** |
|---|---|---|---|---|
| SE1 | 7 250 MW | 5 000 MW | 0.43 SEK/kWh | 96% |
| SE2 | 12 700 MW | 11 000 MW | 0.43 SEK/kWh | 95% |
| SE3 | 16 900 MW | 31 400 MW | 0.67 SEK/kWh | 37% |
| SE4 | 4 350 MW | 8 380 MW | 0.82 SEK/kWh | 50% |

### 4.1.2 Projected excess electricity

Excess electricity constitutes of electricity with no cost as a cause of overproduction of non-adjustable power generation, which can not be used locally or be exported from the current electric area. Today excess electricity is limited due to the dominating base load of nuclear and hydro power, which both can act as a buffer with a relative fast on- and off-ramping in terms of working as a solution for congested transmission and distribution systems (Svenska Kraftnät, 2021). According to a scenario analysis conducted by the Swedish state-owned enterprise Svenska Kraftnät, excess electricity will increase significantly in the coming years with the build-out of renewable energy sources such as wind and solar power. When overproduction occurs, the excess electricity has to be wasted or exported, depending on transmission lines and distribution systems, to electric areas within Sweden or to other neighbouring countries. The four scenarios are constructed for the years 2035 and 2045 and take into account, among other things, future; available electricity storage solutions, growth of power consumption and production, availability of nuclear power, build-out of renewable energy sources, transmission capacity between electric areas, electrification within the industrial sector and transportation sector, and prices for fuels and European Emission Trading System units. Data covering 2025 projections have been sourced from a previous short-term analysis conducted by the same organization in 2020 (Table 4.2) (Svenska Kraftnät, 2021). Since the different scenarios encompasses a variety of uncertainties and assumptions, a median value for each year is used in order to estimate potential use for excess electricity by Bitcoin miners later in the study.

*Table 4.2: Estimated future excess electricity (Svenska Kraftnät, 2021).*

| **Scenario** | **2025** | **2035** | **2045** |
|---|---|---|---|
| Small-scale renewable (SF) | 0 TWh | 1 TWh | 7 TWh |
| Road maps mixed (FM) | 0 TWh | 1 TWh | 6 TWh |
| Electrification planned (EP) | 0 TWh | 0 TWh | 1 TWh |
| Electrification renewable (EF) | 0 TWh | 1 TWh | 16 TWh |
| *Median* | *0 TWh* | *1 TWh* | *6.5 TWh* |

## 4.2 District heating

District heating is the most common form of heating in Sweden and accounts for more than half of all the real estate heating, and around 90% for the heating of multi-family residential houses (The Swedish Energy Markets Inspectorate, 2022). In 2020 the total amount of generated energy for the district heating system amounted to **53.7 TWh**, which is the value used later on in the study. However, it is worth noting that due to losses in the distribution system the total supplied energy to consumer amounted to 46.3 TWh in 2020 (Statistics Sweden, 2021).

District heating is the distribution of heat through extensive networks of water pipes. In the most common systems in Sweden today (3GDH), the water is heated to 70-120°C in a central facility by applying external energy. The heated water is then distributed through well isolated pipes which constitutes the district heating network. The heat is then delivered via heat exchangers into residential blocks, public facilities, and other buildings and the water later returned to the central facility to be reheated (Vattenfall, 2022; Swedenergy, 2020). Next generation district heating systems (4GDH), works in a similar manner but can support lower temperatures for outgoing and incoming water. These systems require water temperatures of around 45-55°C, which is considerably lower than the district heating systems used today (3GDH) (Wahlroos et al, 2018; Lund et al, 2014).

The majority of the energy used to heat the water is generated through the burning of biomass and waste (Figure 4.3). In 2020 the energy mix is estimated to have generated **53.7 g of $CO_2$-eq per kWh** delivered energy, including energy conversion, production, and transportation. It is estimated that 74% of the carbon footprint can be ascribed to the burning of waste and 13% to the use of fossil fuels and peat (Swedenergy, 2022). These values are used in Section 6 when district heating systems are analysed as a potential receiver of waste heat generated by Swedish Bitcoin mining operators.

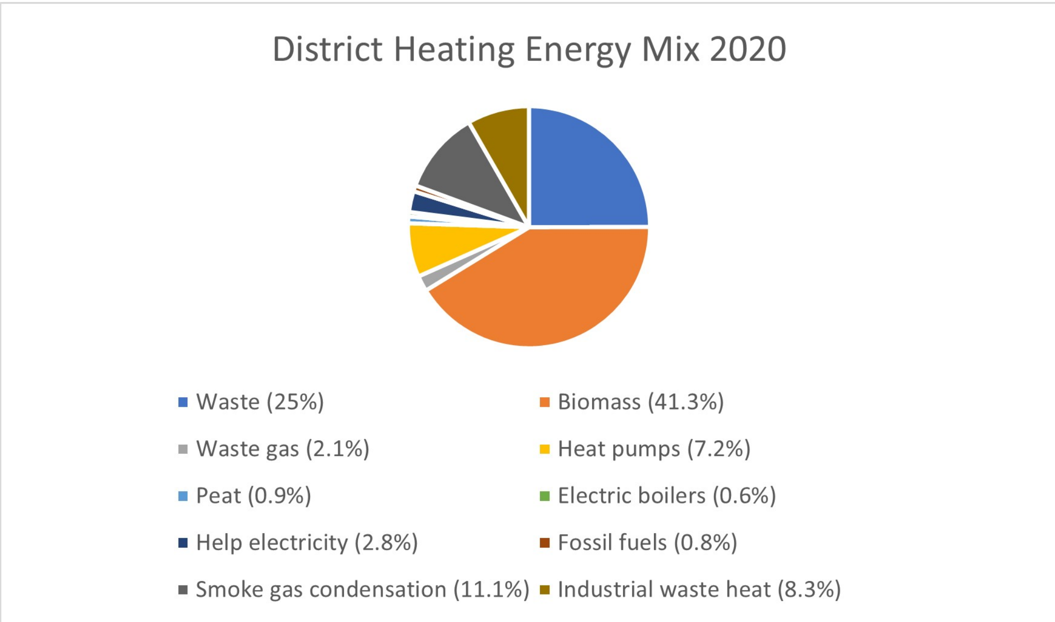

*Figure 4.3: Composition of energy sources for district heating generation in Sweden 2020 (Swedenergy, 2022).*

# 5

# Bitcoin Mining in Sweden

In order to asses the potential implementation of Bitcoin mining in the Swedish energy system, the extent of Bitcoin mining operations in Sweden has to be determined. This is done through triangulating already estimated power consumption and hash rate from literature and generated estimations. Estimated hash rate is then used to generate three cases of mining efficiency in order to account for different technologies and uncertainties as described in Section 3.

## 5.1 Power consumption

The Swedish power consumption of Bitcoin mining is estimated through combining different literature sources and transforming the values into the common unit of TWh per year (Table 5.1). Since there is a certain overlap between these sources (as described in Section 3.3) a mean value is used. The national electricity consumption of Bitcoin mining is estimated to **1.12 TWh per year**, which corresponds to a continuous power draw of 128 MW. This value is used as a benchmark for the different cases generated in the upcoming sections.

*Table 5.1: Literature estimations for Bitcoin mining power consumption in Sweden (CoinShares, 2022; Finansinspektionen, 2021; Cambridge Center for Alternative Finance, 2022).*

| **Power consumption per year** | **Source** | **Time frame** |
|---|---|---|
| 0.70 TWh | CoinShares | Dec 2021 |
| 1.00 TWh | Finansinspektionen | Nov 2021 |
| 1.65 TWh | CCAF | Aug 2021 - Mar 2022 |
| *1.12 TWh* | Mean | - |

## 5.2 Hash rate

The Swedish generated hash rate is estimated by combining different sources and transforming the values into the common unit of TH/s (Table 5.2). Since there is a certain overlap between these sources (as described in Section 3.3) a mean value is used. The hash rate generated in Sweden is estimated to **1 470 000 TH/s**. This value is used to generate the three cases in the next section.

*Table 5.2: Literature estimations for hash rate generated in Sweden (CoinShares, 2022; Cambridge Center for Alternative Finance, 2022a; Blockchain.com, 2022).*

| **Estimated hash rate** | **Source** | **Time frame** |
|---|---|---|
| 1 240 000 TH/s | CoinShares | Monthly mean of May-Dec 2021 |
| 1 690 000 TH/s | CCAF & Blockchain.com | Monthly mean of Aug 2021 |
| *1 470 000 TH/s* | *Mean* | - |

## 5.3 ASIC data

Three cases are constructed in order to calculate Swedish hash rate to national power consumption in order to provide more nuance than the literature value in terms of technology and time effects. This since mining today can be performed with a range of machines with different specifics in terms of energy consumption per hash rate. The most commonly used ASIC as of 2021 in number of units and share of hash rate is the Bitmain Antminer S9 which has been released in several different models since 2015. This older model is used as a worst case based on the extensiveness of its use and its relatively lower efficiency in terms of energy consumption per hash rate. In terms of newer and more energy efficient hardware, one of the most sold machines today is the Bitmain Antminer S19 Pro, released in 2020. Bitmain Antminer S19 Pro is considerably more efficient than the Bitmain Antminer S9, hence this makes up the best case (CoinShares, 2022). These two cases are benchmarked with the mean operational specifics of the entire Bitcoin mining network which is calculated as the weighted average network efficiency. The total network hash rate is calculated by using the average amount of different ASICs in operation during 2021. The number of operational machines is then multiplied with their specific hash rate per unit. By dividing the total network hash rate with the total number of ASICs in operation, a mean value of hash rate per unit is obtained. The calculations are based on data provided by CoinShares and their Bitcoin mining report from 2022. The total network hash rate is benchmarked with the value from Blockchain.com.

From this point in the study, the three cases are notated as Worst Case (Bitmain Antminer S9), Best Case (Bitmain Antminer S19 Pro), and Base Case (Weighted Average Network). Product specifications for the three cases are displayed in Table 5.3, 5.4, and 5.5.

*Table 5.3: Product specifications for Bitmain Antminer S9 (11.5 TH), Worst Case (ASIC Miner Value, 2022).*

| **Bitmain Antminer S9 (11.5 TH) Specifications** | |
|---|---|
| Hash rate per unit | 11.5 TH/s |
| Energy consumption per hash rate | 98 J/TH |
| Optimal temperature | 0-40°C |
| Airflow per unit | 180 cubic feet per minute (CFM) |

*Table 5.4: Product specifications for Bitmain Antminer S19 Pro (110 Th), Best Case (ASIC Miner Value, 2022).*

| **Bitmain, Antminer S19 Pro (110 Th) Specifications** | |
|---|---|
| Hash rate per unit | 110 TH/s |
| Energy consumption per hash rate | 30 J/TH |
| Optimal temperature | 5-40°C |
| Airflow per unit | 400 CFM |

*Table 5.5: Estimated specifications for the Bitcoin network, Base Case (CoinShares, 2022).*

| **Bitcoin Weighted Average Network Specifications** | |
|---|---|
| Hash rate per unit | 30.2 TH/s (weighted average estimation) |
| Energy consumption per hash rate | 59 J/TH (weighted average estimation) |
| Optimal temperature | 5-40°C |
| Airflow per unit | 180 CFM (worst case assumption) |

## 5.4 Heat generation

It is essential to determine the amount of waste heat generated by Bitcoin mining operations in Sweden in order to asses the potential for waste heat recovery and later climate impact.

Based on the ASIC specifications for the Bitmain Antminer S9 and the Bitmain Antminer S19 Pro, an approximation can be made with regards to total heat generation by using the total number of units required for the Swedish generated hash rate and transforming CFM to $m^3/s$. The temperature of the discarded heat is assumed to equal the higher range of the optimal operational temperature, which for all cases lies at 40°C (Table 5.6), this since higher temperatures would decrease efficiency with regards to energy consumption (electricity cost) to hash rate. The Base Case is using the weighted average specifications as described in Section 3.3 while assuming an air flow similar to that of the Bitmain Antminer S9 as a worst case assumption.

*Table 5.6: Estimated continuous waste heat generation for the three cases.*

| **Case** | **Air flow** | **Temperature** |
|---|---|---|
| Worst Case | 10 800 $m^3/s$ | 40°C |
| Best Case | 2 510 $m^3/s$ | 40°C |
| Base Case | 4 110 $m^3/s$ | 40°C |

## 5.5 Estimated electricity consumption in Sweden

By generating the three different cases using hash rate estimations and efficiency specifications for the Bitmain Antminer S9, Bitmain Antminer S19 Pro, and the weighted average network, the following results regarding Swedish Bitcoin mining annual power consumption are obtained (Table 5.7). Note that the Base Case corresponds to the lower interval of the national power consumption according to the literature shown in Table 5.1 and that the mean litterateur value of 1.12 TWh per annum corresponds approximately to the Worst Case. The three cases are here providing some additional nuance which is not displayed in the data sourced from literature.

*Table 5.7: Estimated power consumption for the different cases and comparisons to the total Swedish electricity use of 2021 (139.9 TWh).*

| **Case** | **Power consumption** | **Share of total Swedish electricity use** |
|---|---|---|
| Worst Case | 1.26 TWh | 0.90% |
| Best Case | 0.38 TWh | 0.27% |
| Base Case | 0.76 TWh | 0.54% |

## 5.6 Carbon intensity

Due to the lack of data, the carbon intensity of the electricity used to power Bitcoin miners in Sweden is for simplicity assumed to be that of the Swedish electricity generation, excluding imports and exports, as presented in Section 4.1 of **37.9 g of $CO_2$-eq per kWh**. However, this value is most likely an overestimation. Due to the competitive nature of the Bitcoin mining sector, a large portion of the mining is done in regions with an abundance of cheap electricity, which in the case of Sweden is mainly associated with renewable energy sources, as seen in Table 4.1. This reasoning is also apparent in CoinShares' report from 2022, where the Bitcoin mining operations in Sweden were estimated to have a carbon intensity **19 g of $CO_2$-eq per kWh**. The estimation was made by identifying the location of Bitcoin mining operations in Sweden through a bottom-up approach and by using the regional carbon intensities rather than the national one (CoinShares, 2022). These two carbon intensities are used in order to bring nuance when calculating the climate impact associated with Bitcoin mining operations located in Sweden in Section 7.

# 6

# Bitcoin Mining and Heat Recovery

Bitcoin mining is a flexible operation with regards to geographical location and scale. Mining can be performed in a range from large scale operations with many machines in a structure and scale similar to that of a data centre, to individual machines working on their own. Due to the varying scale of Bitcoin mining operations, this section focus on two different heat recovery situations, one small in the form of a qualitative comparison between an ASIC, a heat pump, and an electric heater, and one larger in the form of a quantitative assessment of the potential integration of Bitcoin mining into the Swedish district heating system. In both cases, all energy consumed by Bitcoin miners in the form of electricity is assumed to turn into heat in accordance with the laws of thermodynamics.

## 6.1 ASIC vs. heat pump vs. electric heater

The comparison for the small case is done in a strict energy perspective looking at one ASIC, one heat pump, and one electric heater from the viewpoint of electricity consumption and heat generation. Other perspectives including economics is instead explored in Section 9.2.1.

Possible heat recovery methods for small scale Bitcoin mining operations include heating of individual homes, apartments, greenhouses, and other simple industrial processes such as drying of crops or firewood. For the small case analysis the heat generation of an individual ASIC is put in relation to that of a heat pump and an electric heater, all machines with a similar use case in the form of heat generation. As stated earlier, the output heat temperature for an ASIC is assumed to be no more than 40°C. Since higher temperatures can be achieved with a heat pump and an electric heater, the analysis is limited to use cases with temperatures reaching a maximum of 40°C.

The energy efficiency of a heat pump can be described by its coefficient of performance (COP), which constitutes the ratio between output heat (J) and input work (J) (Equation 6.1). The higher the COP, the higher the efficiency in terms of needed external energy use. For air-source heat pumps, which are the ones relevant for this study, the COP values are generally ranging between 2 and 4, meaning that they are able to deliver 2 to 4 times more energy than they consume through the movement of heat in space (Dincer  Rosen, 2021). For a processor or a computational machine such as an ASIC, all input energy is exhausted as heat while no heat is actually moved, which is the case for the heat pump. Hence, for comparison, a processor has a theoretical maximum COP of 1 in accordance with the laws of thermodynamics. The same reasoning applies for an electric heater since input energy equals output energy with no movement of heat as in the case of the heat pump. An electric heater has therefore, just as an ASIC, a theoretical upper bound COP value of 1, meaning the same amount of heat is generated per consumed electricity as for the ASIC.

It can be reasoned that the energy efficiency ratio between a heat pump and an ASIC, as well as a heat pump and an electric heater, should be the ratio between their COP values, which as seen previously is ranging between 2 and 4. In climate terms and electricity use, the substitution of heat pumps to ASIC machines, can not provide any positive effects in terms of GHG emission savings all else equal since the ASIC has an energy consumption 2 to 4 times larger than that of a heat pump. However, the substitution of electric heaters with ASICs appears to have a neutral effect on climate considering electricity use and heat generation, with an analysis limited to the use-stage of both machines with heat generation up to 40°C.

In conclusion it appears that an ASIC could be a viable substitute for an electric heater in use cases where the temperature need corresponds to that of 40°C, while a heat pump would be the preferred choice in both cases in terms of electricity consumption and heat generation. The unique attribute associated with the ASIC in this comparison is that while both the electric heater and the heat pump consumes electricity with an associated cost, the ASIC consumes electricity with an associated income. Hence, the comparison between an ASIC, a heat pump, and an electric heater rather becomes an economical one. The economical perspective however, lies outside the scope of this study and is thus not to be further explored besides a revisit in Section 9.2.1.

## 6.2 Integration with district heating

### 6.2.1 Data centers as a proxy

The integration of data centers with district heating in terms of waste heat recovery is something which has been explored in Sweden for some years (The Swedish Energy Agency, 2017). Data centers are a good proxy to Bitcoin mining on a large scale since the set up is similar. In both cases, low grade heat is generated from electric circuits and transported out from the machines via fans. For data centers, air cooling typically generate outlet temperatures between 25°C and 35°C while liquid cooling can reach outlet temperatures of up to 60°C (Koronen et al, 2020). For Bitcoin mining, most ASICs are using air cooling which is also the case for the different ASICs used in this study (ASIC Miner Value, 2022). As seen in Section 5.4 Bitcoin mining outlet temperatures do not exceed 40°C due to decreased operational efficiency in terms of energy consumption to hash rate.

### 6.2.2 Assumptions

In order to utilize waste heat generated by Bitcoin mining in district heating systems, the low grade heat must be upgraded to temperatures around 80°C (3GDH) and 65°C (4GDH). This could be done by using heat pumps and heat exchangers. Outlet temperatures are assumed to be 40°C and the analysis considers two different cases. One in which low grade heat of 40°C is upgraded to 80°C (3GDH), and one in which low grade heat of 40°C is upgraded to 65°C (4GDH). The subsequent heat exchange needed between the heat upgraded air and the water in the district heating system is assumed to have an efficiency of 95% (Andersson, 2022). The study assumes a heat pump with a COP of 3 which could be considered as conservative in reference to other similar studies on the topic (Frisk  Ramqvist, 2018).

### 6.2.3 Calculus

The ratio between heating ($Q_h$) and added work ($W_{in}$), the coefficient of performance ($COP$), is described by Equation 6.1.

$$COP = \frac{Q_h}{W_{in}} \tag{6.1}$$

The thermodynamic notation of $Q_h$ is described by Equation 6.2, where $m$ is the mass in terms of $g$, $c_p$ the specific heat capacity of air in terms of $\frac{J}{g*K}$, and $\delta T$ the temperature difference between in going and out going air which is unit-less.

$$Q_h = m * c_p * \delta T \tag{6.2}$$

Combining Equation 6.1 and 6.2 gives Equation 6.3.

$$COP = \frac{m * c_p * \delta T}{W_{in}} \tag{6.3}$$

Using the ideal gas law (Equation 6.4), $m$ can be substituted via Equation 6.5 and 6.6, to 6.7. Note that for volume, $V$, air flows from Table 5.6 have been used, giving the value of $W_{in}$ the unit $\frac{J}{s}$, W, which is the desired unit for measurement and reference.

$$P * V = n * R * T_0 \tag{6.4}$$

$$n = \frac{P * V}{R * T_0} \tag{6.5}$$

$$m = n * M \tag{6.6}$$

$$m = \frac{P * V}{R * T_0} * M \tag{6.7}$$

Combining Equation 6.3 and 6.7, the following complete expression is obtained (Equation 6.8):

$$W_{in} = \frac{\frac{P*V}{R*T_0} * M * c_p * \delta T}{COP} \tag{6.8}$$

By using the values in Table 6.1, the total additional electricity consumption required for upgrading the waste heat are estimated for district heating systems of the third and the fourth generation. Results are displayed in Table 6.2.

*Table 6.1: Variables and values used in calculations.*

| | |
|---|---|
| Coefficient of Performance, $COP$ | 3 |
| Pressure, $P$ | 101 325 Pa |
| Volume, $V$ | airflow for different ASIC cases from Table 5.6 |
| Ideal Gas Constant, $R$ | 8.314 $\frac{kg*m^2}{s^2*K*mol}$ or $\frac{J}{K*mol}$ |
| Temperature, $T_0$ | 300 K |
| Molar Mass, $M$ | 28.97 g/mol |
| Specific Heat Capacity of Air, $c_p$ | 1.005 $\frac{J}{g*K}$ |
| Change of Temperature, $\delta T$ | 40 & 25 |

*Table 6.2: Additional annual electricity consumption needed for heat upgrade.*

| **Case** | **3GDH (80°C)** | **4GDH (65°C)** |
|---|---|---|
| Worst Case | 1.57 TWh | 0.98 TWh |
| Best Case | 0.37 TWh | 0.23 TWh |
| Base Case | 0.60 TWh | 0.37 TWh |

Figure 6.1 is a graphical visualization of Table 6.2. Note that the blue areas correspond to the waste heat available for recovery.

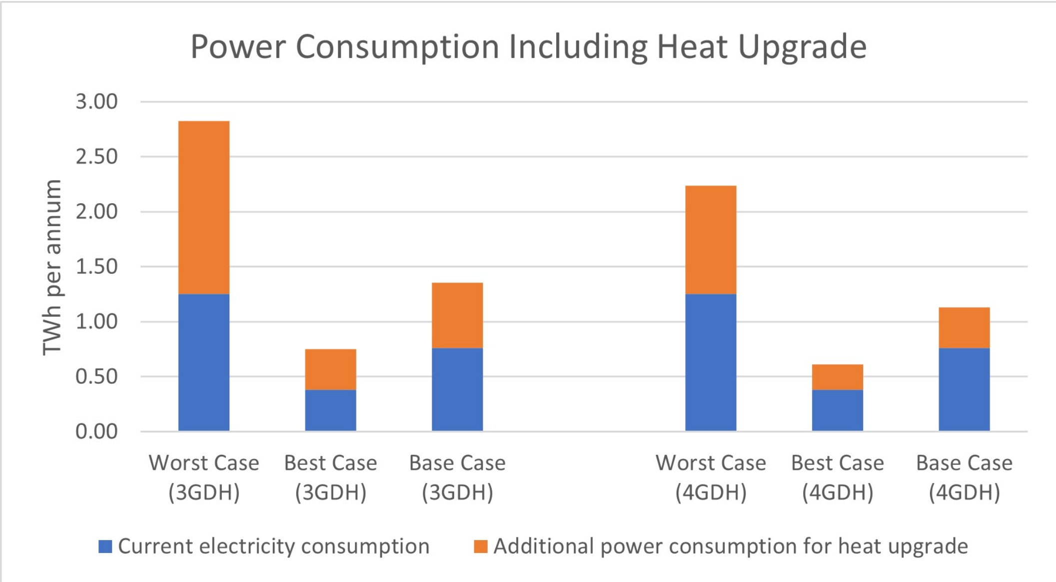


*Figure 6.1: Additional electricity consumption needed for heat upgrade in relation to the estimated Bitcoin mining power consumption. Electricity consumption is expressed as TWh per annum.*

# 7

# Climate Impact

## 7.1 Carbon footprint

The total carbon footprint of current Bitcoin mining operations in Sweden depends on which emission factor that is used. As stated in Section 5.6, two carbon intensities are assumed for Swedish Bitcoin mining operations. One consisting of the carbon intensity of the Swedish electricity generation excluding import and exports, and one carbon intensity estimation provided by CoinShares, taking into account the regional location of Bitcoin mining operations and the corresponding regional carbon intensity. For district heating, the carbon intensity for 2020 is used as explained in previous sections. Carbon intensity values used are displayed in Table 7.1.

*Table 7.1: Carbon intensities used for calculations. Note that the Bitcoin (Swedish electricity mix) is excluding imports and exports.*

| | |
|---|---|
| **District heating, 3GDH & 4GDH** | 53.7 g $CO_2$-eq per kWh |
| **Bitcoin mining (Swedish electricity mix)** | 37.9 g $CO_2$-eq per kWh |
| **Bitcoin mining (CoinShares estimation)** | 19.0 g $CO_2$-eq per kWh |

Using the values for national power consumption estimated in Section 5 combined with the carbon intensity values in Table 7.1. The following results covering the yearly carbon footprint in terms of $CO_2$-eq are obtained (Table 7.2):

*Table 7.2: Estimated annual carbon footprint of Bitcoin mining operations in Sweden based on the three cases and the two carbon intensities.*

| **Carbon Footprint from Bitcoin mining in Sweden (tonnes $CO_2$-eq/year)** | | |
|---|---|---|
| **Case** | **CoinShares estimation** | **Swedish electricity mix** |
| Worst Case | 23 900 | 47 600 |
| Best Case | 7 300 | 14 600 |
| Base Case | 14 400 | 28 800 |

## 7.2 Carbon footprint with district heating integration

### 7.2.1 Heat upgrade

By adding the electricity required for upgrading the generated waste heat needed for district heating integration, the carbon footprint of Bitcoin mining operations in Sweden increases (Table 7.3). The additional electricity used by the heat pump is assumed to have the same carbon intensity as the one for the Swedish electricity mix of 37.9 g of $CO_2$ per kWh in all cases while the electricity used by Bitcoin miners are using the carbon intensity as indicated in Table 7.3.

*Table 7.3: Bitcoin mining carbon footprint including waste heat upgrade for the different carbon intensities. Values are presented as tonnes $CO_2$-eq/year.*

| **Bitcoin mining carbon footprint with heat upgrade (tonnes $CO_2$-eq/year)** | | | |
|---|---|---|---|
| **Case** | **Carbon intensity** | **3GDH** | **4GDH** |
| Worst Case | CoinShares estimation | 83 400 | 61 100 |
| Best Case | CoinShares estimation | 21 100 | 15 900 |
| Base Case | CoinShares estimation | 37 000 | 28 600 |
| Worst Case | Swedish electricity mix | 107 000 | 84 800 |
| Best Case | Swedish electricity mix | 28 400 | 23 200 |
| Base Case | Swedish electricity mix | 51 400 | 42 900 |

### 7.2.2 Substituting current district heating

Assuming no heat recovery from the additional power consumption added by the heat pump for the heat upgrade, and assuming no further energy losses, i.e. input energy equals output energy, the climate impact for substituting current district heating energy sources with waste heat from Swedish Bitcoin mining can be calculated using the general carbon intensity for district heating systems of 53.7 g of $CO_2$-eq per kWh.

Depending on whether Bitcoin mining heat is added to the energy mix as a base load or a marginal load, the practical energy source substitution should reasonably change. Since the burning of waste constitutes an integral part of the Swedish waste management system, this energy source is not likely to be replaced. As seen in Figure 4.3, biomass constitutes the largest relative source of energy, and thus has its separate case in the following section. Subtracting waste and biomass from the district heating energy mix, the most viable energy source available for substitution consists of fossil fuels, amounting to 1.7% (peat and other fossil fuels) of the total total district heating energy generation. This corresponds to 0.913 TWh per annum which is less than the energy supplied by Bitcoin mining in the Worst Case. Further, fossil fuel based energy has a significantly higher carbon intensity than 53.7 g of $CO_2$-eq per kWh. For simplicity, the substitution of current district heating is assuming an energy mix in accordance to Figure 4.3 and a carbon intensity of 53.7 g of $CO_2$-eq per kWh. However, previous discussed points are of relevance and should be noted by the reader. Results covering the substitution of current district heating energy mix with Swedish Bitcoin mining waste heat is displayed in Table 7.4.

*Table 7.4: Annual GHG emissions avoided by substituting current district heating energy mix with Swedish Bitcoin mining waste heat.*

| Case | Energy availible for substitution | Avoided GHG emissions |
|---|---|---|
| Worst Case | 1.26 TWh or 4520 TJ | 67 400 tonnes $CO_2$-eq/year |
| Best Case | 0.38 TWh or 1380 TJ | 20 600 tonnes $CO_2$-eq/year |
| Base Case | 0.76 TWh or 2730 TJ | 40 800 tonnes $CO_2$-eq/year |

### 7.2.3 Substituting biomass with indirect effect

As mentioned in the previous section, a realistic energy source available for substitution with Bitcoin mining waste heat is biomass. Since biomass itself is a renewable resource, the substituting of biomass does not generate any climate impact in terms of reduced GHG emissions. However, biomass could be used in the production of biofuels which could work as a replacement for conventional fuels in the transportation sector, which is heavily dependent on fossil fuels. Hence, the analysis includes a system expansion covering the substitution of fossil fuels by the excess biomass as a consequence of the substitution with Bitcoin mining waste heat.

The composition of the biomass used in district heating systems is mainly in the form of logging residue and other waste products from the forest industry. Logging residues can be used in the production of biomass based fuels such as methanol, ethanol, and HVO (hydrogenated vegetable oil). These can in turn substitute fossil based fuels with a GHG emission savings ratio ranging from 90% to 96% (Becker et al., 2017). Assuming fossil fuels with an emission factor of 83.8 g $CO_2$-eq per MJ, being substituted with biomass (logging residues based ones) with GHG savings of 90%, the total $CO_2$-eq savings can be estimated (Table 7.5) (Becker et al., 2017).

*Table 7.5: GHG emissions avoided by substituting fossil fuels with biomass (logging residues) based fuels substituted with Bitcoin mining waste heat for district heating.*

| Case | Energy available for substitution | Avoided GHG emissions |
|---|---|---|
| Worst Case | 1.26 TWh or 4520 TJ | 341 000 tonnes $CO_2$-eq/year |
| Best Case | 0.38 TWh or 1380 TJ | 104 000 tonnes $CO_2$-eq/year |
| Base Case | 0.76 TWh or 2730 TJ | 206 000 tonnes $CO_2$-eq/year |

By comparing the values from Table 7.4 and Table 7.5 it can be determined that the substitution of biomass with a system expansion provides the largest GHG emissions savings annually (Figure 7.1).

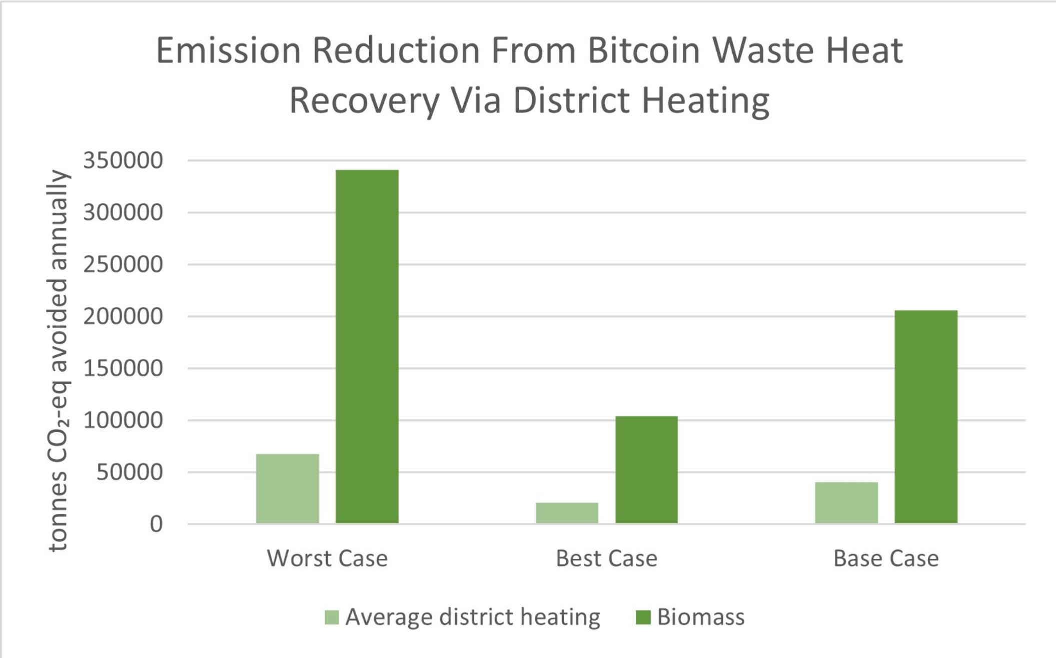


*Figure 7.1: Annual $CO_2$-eq emission savings from Bitcoin waste heat recovery via district heating.*

## 7.3 Usage of excess electricity

As seen in Table 4.2, the estimated amount of excess electricity in Sweden is estimated to grow in the coming years and decades according to all four scenarios provided by Svenska Kraftnät. Using a median value for the four different scenarios, it is estimated that excess electricity will grow from around zero today (2025), to 1 TWh in 2035, and 6.5 TWh in 2045. How large portion of this excess electricity that would be available for Bitcoin miners is not estimated and hard to assess due to different scenarios including effect, location, and other technicalities. However, assuming that the utilization is non-zero, a hypothetical qualitative discussion could be had with regards to the magnitude of excess electricity compared to the national electricity consumption of Bitcoin mining.

The Bitcoin mining electricity consumption of today, ranging between 0.38 TWh to 1.26 TWh for the Best Case and the Worst Case (Table 5.7), could as a maximum grow around 5 times to be exclusively powered by excess electricity. This however is covering a time frame longer than the existence of Bitcoin, which becomes problematic since a historical comparison of the growth of the Bitcoin electricity use might not be relevant. As seen in Section 2.7 estimations for future Bitcoin power consumption are not reliable since it requires one to predict the future price of bitcoin and the future cost and availability of electricity. Hence, a simple forecast is made for the purpose of this study by assuming that the Swedish Bitcoin electricity consumption continues to grow at the same pace as historically, requiring another 0.38 TWh to 1.26 TWh per 13 years (time of Bitcoin's existence), meaning the total power consumption would reach 0.50 TWh to 1.65 TWh in 2025, 0.79 TWh to 2.62 TWh in 2035, and 1.08 TWh to 3.59 TWh in 2045 (Table 7.6 and Figure 7.2).

From this analysis, it is possible that the Swedish Bitcoin mining power demand could by 2035 and 2045 be partly or fully met by excess electricity, reasonable offsetting a corresponding share of the Swedish Bitcoin mining carbon footprint assuming a carbon intensity equal to that of the Swedish electricity generation.

*Table 7.6: Estimated future national Bitcoin power consumption compared to estimated future excess electricity in Sweden.*

| **Scenario** | **Today** | **2025** | **2035** | **2045** |
|---|---|---|---|---|
| Excess electricity | 0 TWh | 0 TWh | 1 TWh | 6.5 TWh |
| Bitcoin power consumption (best case) | 0.38 TWh | 0.50 TWh | 0.79 TWh | 1.08 TWh |
| Bitcoin power consumption (worst case) | 1.26 TWh | 1.65 TWh | 2.62 TWh | 3.59 TWh |

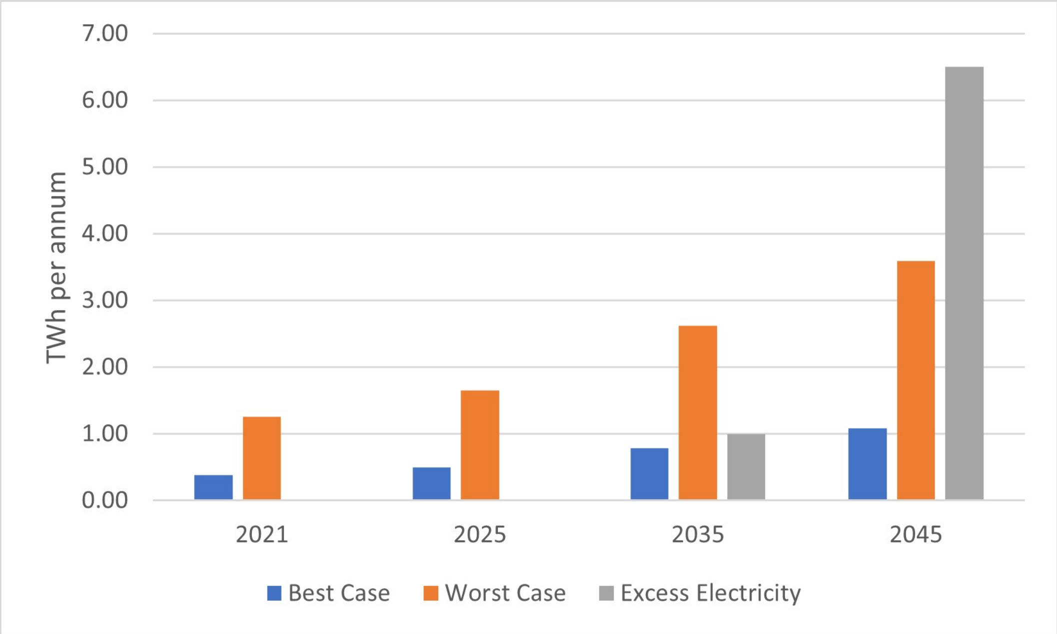


*Figure 7.2: Estimated future national Bitcoin power consumption compared to estimated future excess electricity in Sweden.*

# 8

# Results

## 8.1 Summary

A complete overview of the different cases and their subsequent results are displayed in Figure 8.1.

| POWER CONSUMPTION \ HEAT RECOVERY | | No heat recovery (no heat upgrade) | District heating (3GDH) - average district heating | District heating (3GDH) - biomass | District heating (4GDH) - average district heating | District heating (4GDH) - biomass |
|---|---|---|---|---|---|---|
| Carbon Instensity: Swedish electricity mix | Worst Case | 47 600 | 39 700 | -234 000 | 17 400 | -256 000 |
| | Base Case | 28 800 | 10 700 | -155 000 | 2 200 | -163 000 |
| | Best Case | 14 600 | 7 800 | -76 000 | 2 600 | -81 100 |
| Carbon Intensity: CoinShares estimation | Worst Case | 23 900 | 16 000 | -258 000 | -6 400 | -280 000 |
| | Base Case | 14 400 | -3 700 | -169 000 | -12 200 | -177 000 |
| | Best Case | 7 300 | 500 | -83 200 | -4 700 | -88 400 |

*Figure 8.1: Overview of the results for the different cases. Values are displayed as tonnes $CO_2$-eq annually.*

For comparison, the results displayed in Figure 8.1 can be put in relation to the total national GHG emissions of Sweden, which in 2020 amounted to 46.3 million tonnes $CO_2$-eq (Swedish Environmental Protection Agency, 2022). From the results it can then be determined that the highest estimated GHG emissions from Bitcoin mining operations within Sweden, according to this study, corresponds to 0.1% of the total GHG emissions of Sweden as of today. Similarly it can be determined, using the lowest estimated GHG emissions from Bitcoin mining operations within Sweden from this study, that the total Swedish carbon footprint could potentially be reduced by roughly half a percent in a scenario with full heat recovery through district heating integration (4GDH) and additional biomass substitution via a system expansion.

## 8.2 Analysis

As expected, the carbon footprint decreases significantly in all cases when assuming a lower carbon intensity (CoinShares' estimation at the bottom part of Figure 8.1). The largest reduction of the Swedish Bitcoin mining carbon footprint is achieved when biomass used in the generation of district heating is substituted by Bitcoin mining waste heat and then used to replace fossil based fuels used for example in the transportation sector. In the biomass cases, the values do not differ significantly on a relative basis between 3GDH and 4GDH. This is a result of the enormous GHG emission savings generated by replacing biomass which is dwarfing the carbon footprint associated with national Bitcoin mining in the system expansion scenario.

It is also apparent that waste heat recovery is essential in order to reduce the Swedish Bitcoin mining carbon footprint. Even though the different heat recovery methods differ in terms of the quantity of avoided GHG emissions, all cases provide a reduced carbon footprint compared to the "no heat recovery" cases. This despite that all heat recovery cases require a heat upgrade which is associated with additional power consumption and GHG emissions as compared to the the "no heat recovery" cases which does not need waste heat upgrading.

Further, heat recovery via 4GDH is not surprisingly more efficient in terms of electricity consumption and GHG emissions compared to 3GDH. This as a consequence of the reduced power use associated with the reduced need for heat upgrade due to the lower temperature requirements.

Studying the different cases covering national electricity consumption, there appears to be a optimum where the amount of supplied waste heat triumphs the associated Bitcoin mining power consumption and associated GHG emissions. For example in the columns to the right in Figure 8.1 where the Base Case shows a lower relative carbon footprint compared to the Best Case.

# 9

# Discussion

## 9.1 Data uncertainty and system boundaries

The first object for discussion, and something which has been pointed out many times throughout the study, is the uncertainty associated with the data, including assumptions, time effects, and coverage. Data used in the study covers a relatively short time frame which means that the results should be viewed as a snapshot of the current situation and subject to change with the fluctuations of the price of bitcoin as well as the cost and availability of electricity.

The extensiveness of Bitcoin mining operations are heavily dependent on the bitcoin price and cost of electricity, both of which tend to fluctuate during time. Hash rate and national electricity consumption are mere estimations which do not cover the complete picture, as explained in Section 3.3. Since the results are based on these estimations, potential data errors are transferred throughout the study. However, since multiple cases have been used in the report, a margin should have been provided in the difference between the Worst Case and the Best Case, which should account for some of the uncertainties associated with the raw data.

Data covering the Swedish energy system, electricity generation, district heating, and carbon intensity are also subject to uncertainties due to the short time frame. However, the fluctuations of these data points are relatively small in comparison to those of the Bitcoin electricity consumption, hash rate, and the price of bitcoin, and should therefore not have a significant altering effect on the results on a relative basis.

Further, time effects are in part taken into consideration through the use of the three Bitcoin mining cases, the comparison between 3GDH and 4GDH, and the analysis of the future use case of excess electricity. Overall, the different cases and scenarios should in combination with each other reduce some of the most significant uncertainties and variations associated with the different aspects discussed above by the range of results displayed in Figure 8.1. It is nonetheless important to again point out that the study is limited to the use-stage of Bitcoin mining in Sweden. Hence, no further system expansions are taken into account, except in the case of substituting fossil based fuels with biomass based ones, meaning that the effects of sourcing of raw material, transportation, waste management, and other processes outside the use-stage are not accounted for in the results.

## 9.2 Technology

### 9.2.1 ASICs and mining operations

As in many other emerging sectors, perhaps especially within technology and software, innovation and development is progressing in a rapid pace. This is somewhat illustrated in the different cases of Bitcoin mining machines (ASICs), referred to in the study as the Worst Case, Best Case, and Base Case. The ASICs used for the Worst Case and the Best Case, with only roughly five years between their respective releases, show very different performance in terms of energy consumption per hash rate. During the time of the writing of this thesis, newer and more efficient machines has emerged such as the Intel Blockscale ASIC which is consuming 26 J/TH, an almost 15% improvement compared to the Bitmain Antminer S19 Pro used in the Best Case.

Bitcoin mining is ultimately an economical activity, driven by profit maximization, seeking to reduce capital and operating expenditures (CAPEX and OPEX). Economical incentives for increasing the durability and longevity of ASIC machines could in time decrease CAPEX on a relative basis compared to OPEX for Bitcoin mining operators. An increased importance of OPEX means that auxiliary income streams which can reduce OPEX will become more important, for example making Bitcoin mining more dependent on waste heat recovery income streams apart from the Bitcoin block reward and the inherent transaction fees. In a scenario like this, a Bitcoin miner could make waste heat into a resource, as it helps monetize electrification, creating an income stream that is generated by producing heat which could be sold on a secondary market. It is also reasonable to assume that the global sustainability agenda, upcoming regulation, as well as innovation and future business opportunities might push development for ASICs optimized for heat recovery, for example ASICs which can deliver waste heat with higher temperatures than the 40°C of today. This means in turn that ASICs could in time become a viable option to electric heaters as already discussed in Section 6.1, since they share the same energy efficiency in terms of COP, i.e., the same amount of energy is converted from electricity to heat in both cases. With time this could mean that eventually all electric heating applications and machines could in theory be substituted with ASIC machines, even though a heat pump is the preferred choice from an environmental point of view. ASICs do not only have the same electricity to heat performance as an electric heater (from a use-stage perspective), but also have an income associated with the heat generation while an electric heater has an associated cost for generating heat. Hence, from an economical perspective, all else equal, the transition from electric heating to ASIC based heating appears to be inevitable provided ASICs manages to catch up with the technical performance of electric heaters in terms of delivering higher output heat temperatures. Further, the same economical reasoning could be applied to the comparison between an ASIC and a heat pump. A heat pump however, will have a significantly lower environmental impact due to its operational specifics, which means that the substitution of heat pumps with ASICs would only be for economic reasons.

It could also be reasoned that since Bitcoin mining operators are constantly trying to increase the number of computations per unit of energy, spillover effects could occur in the general hardware sector. Meaning that Bitcoin mining potentially could be driving energy efficiency (computations per energy unit) throughout the whole hardware industry.

### 9.2.2 District heating and mining integration

Technological development within district heating is driving efficiency higher in terms of lower required temperatures, for example in the move from 3GDH to 4GDH. It can hence be reasoned that the temperature spread between the waste heat generated by Bitcoin miners and the heat requirements associated with district heating systems is tightening. This effect should be even stronger when assuming the potential emergence of ASIC machines more optimized for heat recovery and waste heat utilization with higher output temperatures, as discussed in the previous section. With this background it could be reasoned that the prospects for the integration of Bitcoin mining, as well as data centers, with district heating systems should be improving with time as the need for upgrading the generated heat is reduced. This is also indicated by the results when comparing 3GDH and 4GDH, which suggest that the heat upgrade and the size of the temperature difference between the supply and demand of heat is a determining factor for the feasibility of heat recovery from a climate perspective. The feasibility should also improve from an economical perspective considering that the upgrading of heat is associated with a cost for running the heat pumps. Elaborating on this scenario, with a larger utilization of waste heat within district heating systems due to the dynamics discussed above, Bitcoin mining could potentially provide incentives for the electrification of the Swedish energy grid as Bitcoin mining and data center waste heat is substituting other energy sources such as fossil fuels and biomass. Important to note here is that the move towards more energy efficient district heating systems is also improving current methods for supplying heat for example through the burning of waste and biomass, which are to be put in comparison to the alternative of using Bitcoin mining waste heat. This could potentially reduce the prospects for integrating Bitcoin mining in district heating systems both from an environmental and economical perspective.

The electrification of the district heating system however is somewhat already apparent with an increased use of electric heaters and heat pumps for supplying heat. This as a result of costs and an increased demand for biomass from other sectors. As discussed above, the utilization of Bitcoin mining waste heat should reinforce this tendency due to the economical dynamic associated with Bitcoin mining. It is however important to note that current district heating energy supply is also dependent on economics, including the price of electricity, biomass, and other energy sources for generating heat.

## 9.3 A changing energy system

With the build-out of renewable energy sources such as wind and solar, fluctuations and grid instabilities are expected to increase as the relative share of stable base load is decreasing. There are some studies suggesting the use case of Bitcoin mining as a demand response tool for balancing the grid. For example in Texas where Bitcoin miners are working together with the Electric Reliability Council of Texas (ERCOT) in order to bring stability and balance to the electricity grid. Bitcoin miners additional load on the electricity grid can work as a buffer when electricity production is low by turning of the miners and hence decreasing the demand which then can better meet the supply, reducing price fluctuations and grid instabilities. So called intermittent mining. This could for example be relevant during extreme weather events, cold winters, temporary supply disruptions or in a future scenario where renewable energy such as wind and solar has a larger share of the electricity generation. A scenario like this would require further integration of Bitcoin mining operations in the energy system, for example with district heating, as explored in this study, or perhaps combining Bitcoin mining with data centers or power plants, allowing power supply operators to better manage their energy production resources. With this background there could be an increased need for regulatory measures and economical incentives for supporting Bitcoin miners to work with the energy grid, such as in the Texas example, this in order to provide stability and reduce fluctuations. However, due to the economics of mining, a decreased supply of electricity on the grid would automatically mean higher prices, which in turn would make it less profitable to mine, meaning that market forces should reasonably make Bitcoin miners work as a tool for demand response already, making it a self-regulating system controlled by market signals. Further, an increased integration of Bitcoin mining in the Swedish energy system could perhaps also increase data visibility and transparency in the Bitcoin mining space and the sector in general, something which is needed.

The most promising application for Bitcoin mining in Sweden seems to be in the northern regions where there is a large supply of cheap renewable electricity (as seen in Table 4.1), as well as a large demand for heating due to the colder climate, especially during the winter season. The same should hold true for countries with a similar climate and energy system as that of Sweden, for example Norway and Canada. As suggested in this study, Bitcoin mining operations in these areas could potentially provide large GHG emission savings, especially if excess electricity is used for Bitcoin mining, generating heat which could be used in district heating systems, substituting fossil fuels or biomass which in turn could be used for other societal functions.

Further, with a limited transmission capacity between the different electric areas of Sweden, Bitcoin could from perhaps a more philosophical view be seen as a tool for energy transfer. Just like aluminum smelting or hydrogen generation move energy from one area to the next in the form of molecules in the physical world, Bitcoin mining could move energy through bits in the digital realm, working as a money battery or a digital transmission line. Even though this is from a highly speculative and philosophical view point, the perspective becomes relevant when for example comparing the build-out of transmission lines with the option of "exporting" the energy in the form of bitcoin, aluminum, or hydrogen.

## 9.4 Economics of Bitcoin mining

As somewhat already discussed in the previous sections, Bitcoin miners operate under unique economic dynamics which make them a special kind of electricity consumers. Bitcoin miners are location agnostic and operations can be established anywhere in a variety of scale as long as internet connection and electricity is available. This is a relevant property when it comes to the utilization of waste heat since Bitcoin miners can be placed in areas where heat demand is high and can be quickly relocated if needed. Another aspect which is unique with Bitcoin mining is that it is an interruptible process. Since the operations are electricity intensive, meaning almost all OPEX is associated with the electricity costs, Bitcoin miners can adjust their consumption without extra cost (except the alternative cost for mining), making them ideal for demand response as discussed above.

The global and competitive dynamics of Bitcoin mining leads to a constant pressure towards trying to access cheaper and cheaper electricity, meaning that Bitcoin miners reliant on expensive electricity will eventually be forced out of the market by miners with access to cheaper electricity. This means that Bitcoin mining should in time, by default, be located towards areas with the lowest cost of electricity. The demand for lower electricity costs (OPEX) could mean that Bitcoin mining operators who are just plugging into the electricity grid without positively contributing to the energy system may not be economically viable in the long term, making heat recovery, demand response, and other ancillary services a requirement in order for staying competitive and surviving in the space if these measures are economically viable. This could also include utilization of stranded energy sources which can provide low electricity costs due to low or no demand. Stranded energy sources could include current energy sources or renewable energy under build-out with limited transmission capacities, but it could also include fossil based energy sources such as off-grid oil and gas deposits.

## 9.5 Regulation

The prospects for integrating Bitcoin mining in the energy system seem promising, especially when considering future technological developments. From the results obtained in this study, there appears to be reasonable arguments towards trying to integrate Bitcoin mining operations within the Swedish energy system, using miners as a supplier of heat as well as a potential consumer of excess electricity. However, since Bitcoin mining operations with no heat recovery system do in fact contribute to higher national GHG emissions, it could be reasonable from a regulatory stand point to incentivize Bitcoin mining operations to consume renewable energy and excess electricity. Further it can be reasonable to require Bitcoin miners located in Sweden to make use of their waste heat, for example demanding operators to provide plans for how the waste heat is recovered and for what purposes. These measures could be put into action by both economic and administrative instruments, for example by taxing miners using fossil based energy sources, or subsidising mining operations with environmentally effective heat recovery schemes. This is true for Sweden as well as for the European Union from a global perspective.

Since Bitcoin mining is a highly competitive industry where cost efficiency is key, Sweden and the European Union could by incentivizing mining operations within their territories potentially drive out Bitcoin mining operations located in other countries with larger fossil fuel dependence, hence potentially decreasing the global carbon footprint of the whole Bitcoin mining industry. If Sweden and the European Union becomes the cheapest and cleanest place for Bitcoin miners to operate, Bitcoin miners would eventually reallocate from countries with higher electricity prices and higher carbon footprints. With the same reasoning, a ban of Bitcoin mining within Sweden or the European Union could, just as suggested by Juhlin, increase the GHG emissions of Bitcoin mining globally when indirectly stimulating mining operations in other countries by increasing the relative income stream to electricity costs. It appears that a complete ban of Bitcoin mining in Sweden and in the European Union, as suggested by Risinger and Thedéen, does not seem to be aligned with neither the actual extensiveness of Bitcoin mining operations located in Sweden, nor with the economics of Bitcoin mining and the potential use of Bitcoin miners as suppliers of heat and consumers of excess electricity, but rather an arbitrary political claim. Instead, focus should be put towards building more cheap and clean electricity within Sweden and the European Union as well as finding smart, economically viable, and environmentally effective solutions for integrating Bitcoin mining operations in such a manner that the whole energy system is benefiting.

## 9.6 The value of Bitcoin

The ultimate question when discussing Bitcoin and Bitcoin mining is what underlying use case and value is provided to the society and to the individual. As described in the introduction, assuming Bitcoin has no value, all energy used to secure the network could be seen as a waste. Likewise, assuming Bitcoin has a value, or to its extreme, that Bitcoin is the new monetary system which will provide freedom and justice to humanity, probably a lot more energy should be allocated towards securing the network. It all comes down to the somewhat philosophical question of what value and utility is, both on an individual level and on a societal level. It could be argued that the data centers and servers powering Netflix, Facebook, and TikTok provides no more value than the Bitcoin network, and there are even studies suggesting that some of these applications on the contrary have negative overall effects on society, but for some reason the energy use of Bitcoin seems to get most of the media attention.

In the case of Bitcoin, the discussion of what money really is also becomes relevant. However, multiple works have already been done on this subject which ultimately lies outside the scope of this report, hence that question will be left for the readers to explore on their own.

# 10

# Conclusion

As with many complicated topics, the answers easily have a tendency to land in a "it depends". Looking at the questions articulated in the beginning of the study one by one, this becomes apparent.

**What is the climate impact of integrating Bitcoin mining in the Swedish energy system?**
Integrating Bitcoin mining in such a manner that cheap renewable or excess electricity is utilized in combination with heat recovery, positive climate impact can be achieved in terms of decreased national GHG emissions, for example using excess electricity for Bitcoin mining in areas with a large heat demand and established district heating systems. However, Bitcoin mining operations with no method for heat recovery do have a negative effect by increasing national GHG emissions, which is making regulation that is incentivizing the use of smart heat recovery methods as well as the use of renewable and excess electricity essential.

**What are the prospects for utilizing waste heat generated by Bitcoin miners in the Swedish energy system?**
Waste heat generated by large scale Bitcoin mining operations could be recovered through the district heating system with the help of upgrading the heat via heat pumps. Depending on the carbon intensity of Bitcoin mining operations and what other energy sources are substituted in the district heating generation, both negative and positive GHG emissions can be achieved. Further, Bitcoin miners could in the future become a viable substitution for conventional electric heating as they share the same performance in terms of electricity to heat while the miner is more attractive from an economical perspective.

**What are the prospects for using excess electricity generated in Sweden for Bitcoin mining?**
Based on the scenarios provided by Svenska Kraftnät, there appears to be a case for the utilization of excess electricity by Bitcoin miners. However, this would be for the years 2035 and 2045 and is hence subject to many different uncertainties.

# 11

# Future Research

The Bitcoin space is a fast moving one. During the writing of this thesis, a second country has adopted bitcoin as legal tender (the Central African Republic), the EU has had a voting on banning cryptocurrency mining using proof-of-work (a suggestion which did not pass), and new promising technologies have been developed. No matter how exciting the fast pace of the space is, it ultimately makes the creation time proof and reliable analysis around the topic difficult. The subject of Bitcoin is a multidisciplinary one which will require multiple studies within a number of different fields and domains in order to uncover all the nuances and perspectives associated with the technology.

One important aspect which has not been within the scope of this study is the broader perspective of resource use and environmental effects. A Bitcoin miner is a complex electrical unit which requires different materials, metals, and minerals. The global problem of electronic waste is rapidly growing and the lack of insight in the waste management processes as well as the lack of reliable recycling methods are just some of the associated problems. Hence future studies looking at Bitcoin miners and ASICs through a life cycle assessment perspective would be of great interest in order to asses the total climate and environmental effects associated with the Bitcoin mining industry.

Another interesting aspect not covered in this study is the alternative cost of electricity use. Would it for example be more effective from a climate perspective to export the electricity used by Swedish Bitcoin miners to countries more dependent on fossil fuels, or would it be more effective to let Bitcoin miners use the electricity in order to drive out miners in markets with a higher dependence on fossil based energy sources.

Further, due to the relative uniqueness of the economic landscape in which Bitcoin miners operate, studies focusing on the economic aspects associated with the Bitcoin mining industry would be of great interest, including studies looking at the economical effects of integrating Bitcoin mining operations with the conventional energy system, its effect on the electricity grid, electricity prices, electricity production and consumption, as well as distribution and transmission. Within the same domain, studies focused on waste heat as a product or resource would also be of interest. Further, economical analysis with regards to the comparison between ASICs and conventional electric heaters would also provide further insights to the Bitcoin mining industry. Economic analysis could also encompass operating time, present and future comparisons between CAPEX and OPEX, taxation, and other regulatory barriers and/or incentives.

This study has solely been focusing on Sweden, a country with a high share of renewable energy, relatively cheap electricity, a net positive balance of electricity generation (electricity exporter), and a cold climate with a large demand for heat. Hence, the results in this study are skewed for the specific conditions of Sweden. Future studies focusing on other countries with different energy systems and climates are therefore of great need in order to provide further perspectives of the Bitcoin mining industry. For example, how would Bitcoin mining affect the energy system in a country with a larger dependence of fossil fuels and located in a tropical climate.

Lastly, studies analyzing the effects of technological progress would also be of interest, focusing on improved ASICs and district heating technologies as discussed in Section 9.2.1, including scenario analysis and comparisons with other technologies with similar features and properties.

# 12

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