MASTER´S THESIS

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Bitcoin mining as a demand response in an electric power system: A case study of the ERCOT-system in Texas

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Sammendrag

I tradisjonelle energisystemer var tilbudssiden ansvarlig for å tilby fleksibilitet. En økende grad av sol og vind i moderne energysystemer reduserer tilbudssidens fleksibilitet og presser dette ansvaret over på etterspørselssiden. Derfor blir det stadig viktigere med fleksible energikonsumenter som kan tilby etterspørselsfleksibilitet for å stabilisere nettet.

Denne masteroppgaven studerer de distinktive karakteristikkene av bitcoin mining som etterspørselsfleksibilitet og hvordan disse faktorene vil påvirke fremtiden av bitcoin mining som en slik mekanisme. Disse faktorene ble identifisert gjennom en case-studie av bitcoin mining som etterspørselsfleksibilitet i ERCOT-systemet i Texas, hvor dataene ble kvalitativt hentet og analysert. Et rammeverk med positive og negative faktorer ble utviklet fra funnene, og er det største bidraget til litteraturen.

Hovedfunnene fra case-studien er en beskrivelse av de positive og negative faktorene for å benytte bitcoin mining til etterspørselsfleksibilitet. De positive og negative faktorene er gruppert inn i tekniske, økonomiske, politiske og miljømessige grupper. Bitcoin mining er, basert kun på de tekniske faktorene relatert til hvordan prosessen konsumerer elektrisitet, veldig godt egnet til etterspørselsfleksibilitet. Som forklart i oppgaven er bitcoin mining en energi-intensiv og stabil belastning som hurtig kan justeres opp eller ned med ekstrem presisjon, uten ekstra kostnader. Internettforbindelse og tilgang til elektrisitet er de eneste geografiske kravene, så bitcoin minere er også ekstremt geografisk fleksible og kan enkelt slå seg ned akkurat der hvor etterspørselsfleksibilitet trengs mest. Andre positive faktorer kommer fra den miljømessige gruppen, siden den stabile og avbrytbare belastningen bitcoin mining gir kan hjelpe til med å integrere fornybar energi.

De negative faktorene kommer hovedsakelig fra den økonomiske og den politiske gruppen. Bitcoin mining er en relativt ny industri, noe som kommer med sine utfordringer. Bitcoin prisen er volatil og det fremtidige produksjonsvolumet til en bitcoin miner er også usikkert og per nå er nødvendige verktøy for hedging enda ikke utviklet og

implemtert i bransjen. I tillegg er bitcoin mining under kritikk på grunn av sitt store elektrisitetskonsum, og møter også motstand fra enkelte lands myndigheter.

Problemstillingen er viktig i en global sammenheng siden fremtidens energisystemer preget av mye variabel fornybar energi trenger fleksible konsumenter. Det eksisterer lite literatur på området, men funnene i masteroppgaven understøtter den beskjedne literaturen som finnes om bitcoin mining som etterspørselsesfleksibilitet.

Abstract

In traditional energy systems the supply-side was responsible for providing flexibility. An increasing share of wind and solar in modern energy systems reduces the supply-side's flexibility and pushes these responsibilities over on the demand-side. Therefore, the need for flexible energy consumers offering demand response solutions to stabilize the grid is rapidly increasing.

This master thesis studies the distinctive characteristics of bitcoin mining as a demand response and how these factors will influence the future of utilizing bitcoin mining as this mechanism. These factors were found by conducting a case study of bitcoin mining as a demand response in the ERCOT-system in Texas, where the data was collected and analyzed qualitatively. I created a framework with enabling and constraining factors from the findings, which adds to a gap in the literature.

The main findings from the case study is the identification of enabling and constraining factors for utilizing bitcoin mining as a demand response. The enabling and constraining factors are broken down into technical, economical, political and environmental groups. The electricity consuming process of bitcoin mining is, judged purely on its technical power consumption characteristics, very suitable as a demand response mechanism. As explained in this thesis, bitcoin mining is an energy intensive and stable load that can be rapidly adjusted up or down with extreme precision, at no extra costs. With internet connection and access to electricity as the only geographic requirements, bitcoin miners are also extremely geographically flexible and can easily locate themselves exactly where demand flexibility is needed. Other enabling factors come from the environmental group, since the stable and interruptible load of bitcoin mining can help integrate renewable energy.

Although bitcoin mining scores extremely well on the technical factors, it also has some constraining factors coming mainly from the economical and political groups. Bitcoin mining is a relatively new industry, which comes with its challenges. The bitcoin price is volatile and the production volume of a bitcoin miner is also uncertain, and the necessary hedging tools are yet to be developed and implemented in the industry. In addition, bitcoin mining is often scrutinized for its high electricity consumption, as well as attracting the wrath of certain governments.

The problem statement is important from a global viewpoint since the energy systems of the future characterized by a lot of variable renewable energy needs flexible consumers. Little literature exists in this field, but the findings in this master's thesis supports the existing literature about bitcoin mining as a demand response.

Preface

This master thesis marks the end of my studies at the Master of Science program in Energy Management. The program is a joint degree between Nord University in Bodø, Norway and Moscow State Institute of International Relations (MGIMO) in Russia.

I have been fortunate enough to get the opportunity to combine energy related topics I have learned during my degree with one of my main interests: Bitcoin. I was hoping that I could find a way to combine these topics in my master's thesis, so before writing my thesis, I contacted Bendik Schei from Arcane Research, and he put me in touch with the bitcoin mining expert Christopher Bendiksen. He helped me brainstorm topics for research and gave me inspiration for my problem statement. He also gave me guidance during the research process and put me in touch with industry insiders. Writing this thesis without his help would have been very difficult.

I would also like to thank industry insiders I have spoken to from Texas. Bitcoin mining as a demand response is a very niche topic with little publicly available information. Therefore, the information and expertise provided by them has been invaluable. I feel grateful that people from the industry, who I know are very busy in building their businesses, have shown interest in my thesis and taken the time to speak to me.

And before anything, I would like to thank my supervisor Professor Petter Nore. His decisive guidance and support has been invaluable in writing this thesis, and has led me through the chaotic process that academic writing can be. In addition, I would also like to express my gratitude to other professors at Nord University, who also have given me some advice and input, and I appreciate the faculty's intellectual openness and curiosity regarding new concepts like bitcoin mining.

Tbilisi, Georgia. 21.05.2021

Jaran Mellerud

Table of Contents

List of figures

List of tables

1 Introduction

1.1 The backdrop for bitcoin mining as a demand response

The International Energy Agency has estimated that the global capacity of all forms of demand-side flexibility must increase by a factor of ten by 2050 in order to reach their Sustainable Development Scenario (IEA, 2020; Demand Response). The main reason why such an increase is needed is that with a growing share of uncontrollable and variable renewable energy in the energy mix, the demand-side must provide a larger share of the flexibility needed in the system. Demand-side flexibility can come from batteries, hydrogen, pumped hydro, transmission or demand response. As defined by Li et al. (2015):

"Demand Response refers to changes in electric use by demand-side resources from their normal consumption patterns in response to electricity price changes, or to incentivize payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized."

Since existing infrastructure for demand response already exists, it is considered cheaper than the other demand-side flexibility solutions (Li et al., 2015). Demand response can mainly be provided by energy intensive industry, since their energy consumption is concentrated and can be coordinated more easily than households'.

One promising industry for demand response is the data center industry, and more specifically bitcoin mining. During the last few years, we have seen a massive growth in this energy-hungry sector globally, and CBECI (2021) estimates it to consume around 140 TWh annually. As will be explained in this thesis, bitcoin mining is a flexible and interruptible load, and is already providing demand response services in the ERCOT-system in Texas, as well as being used as other energy tools in other regions globally, as explained in chapter 6.2.

1.2 Motivation for research

My motivation for selecting this topic of research is diverse. First of all, my master's program in Energy Management has had extensive coverage of the global energy transition where renewable energy is gradually replacing fossil fuels in the energy mix. The huge challenges of this transition caught my attention, as I realized that the biggest challenge in the energy transition is not about building out sufficient capacity, but in replacing the lost supply-side flexibility with demand-side flexibility solutions like batteries and demand response. This realization sparked my interest in energy systems.

My relationship to bitcoin had a more bumpy start. A friend first pitched it to me as an investment opportunity in 2013 at around $100, but I was certain it was a fraud and condemned it so hard that not only I, but also he refrained from investing in it. The next time bitcoin caught my eye was during the summer of 2017 when another friend had invested, and I started to read about it online. I still did not understand it properly, but I invested sporadically in bitcoin between this year and 2020, often buying at tops and selling at bottoms. In the spring of 2020, after questioning the massive currency printing of the U.S. Federal Reserve in response to covid, I decided to spend time to properly understand Bitcoin and other forms of money, and I studied it full time during this summer. Since mining plays a foundational role in how Bitcoin works, a considerable amount of this study time was spent researching it, and I became particularly interested in the competitive dynamics in the bitcoin mining sector and how it relates to energy. Electricity is the largest operational cost component of a bitcoin miner, and the industry is ultimately competing only on costs. Therefore, in order to stay profitable in the long-term, a miner must have access to cheaper electricity than its competitors, which pushes them to seek out cheap, underutilized energy, often in remote locations, since they are able to locate themselves almost anywhere. This is extremely fascinating for me, as it presents a number of innovative opportunities for utilizing Bitcoin miners as integrated tools in various energy systems.

Since I was obsessed with Bitcoin and enjoyed spending time researching it, I realized that I should find a way to write my Energy Management master's thesis about it in order to unite my main interests. There were several choices in how to combine bitcoin mining and energy into a master's thesis, and I discussed these choices with an industry insider named Christopher Bendiksen, and he pointed me in the direction of bitcoin mining as a demand response using the ERCOT-system in Texas as a case study. This topic was then chosen since it perfectly aligns bitcoin mining with grid flexibility, which is my biggest interest from my master's program in Energy Management.

Bitcoin mining as a demand response is a new field where limited research has been conducted. Therefore, the overall goal of this thesis is to provide a base for further research into the topic, where this thesis can serve as an overview so that other researchers can go more into the details. Another aim is for this thesis to help professionals and regulators from the energy sector learn more about bitcoin mining and how it potentially can be integrated as a grid stabilization mechanism, as well as shedding light on cost-saving opportunities for professionals from the bitcoin mining sector.

1.3 Research question

The main focus of the thesis lies in analyzing bitcoin mining as a demand response in the context of the ERCOT-system in Texas. I am looking to investigate how suitable bitcoin mining is as a demand response, considering both the process' technical, economical, political and environmental characteristics. These characteristics will in the end of the thesis be divided into enabling and constraining factors and summed up in a table. To assess the technical suitability of bitcoin mining as a demand response, we first need to know what technical factors to evaluate it on. The technical factors will be put together in a framework for evaluating the technical feasibility of different processes for use as demand response. I hope this framework not only can be used on the bitcoin mining industry, but on other industries as well, as the need for industries to participate in demand response is rapidly growing. The technical factors related to how a process consumes energy are clearly the most important, but I will still go through economical, political and environmental factors of the Bitcoin mining industry to give my analysis more depth and show the readers more aspects of the industry. Thus, I propose the following research question:

What are the enabling and constraining factors for utilizing bitcoin mining as a demand response in an electric power system?

1.4 Outline of the master’s thesis

Chapter 1 introduces the backdrop for bitcoin mining as a demand response and why innovation in demand response technology is needed. Also, this chapter contains a description of my background in the topic and why I chose to write my master’s thesis about it. In addition, the limits of the research is defined by proposing a research question.

Chapter 2 provides relevant theory about the research topic. This theory mainly comes from the fields of demand response, Bitcoin and bitcoin mining. In this chapter, a framework which will be used to evaluate Bitcoin mining as a demand response is provided.

Chapter 3 describes the research design that was chosen for my case study, along with the data collection methods and how the data was analyzed. The chapter also contains an evaluation of the research limitations through reliability and validity.

Chapter 4 introduces the case of the ERCOT-system in Texas, where important characteristics of this electricity market is provided. A short description of how demand response is working in Texas is given, along with an account of the two main ways Texas’ bitcoin miners can provide demand response services to the grid.

Chapter 5 shows the empirical findings from the case study and divides the material up into different factors which will be further analyzed. The factors are technical, economical, political and environmental.

Chapter 6 the empirical findings are discussed more into depth and the research question is addressed.

Chapter 7 comes with a conclusion of the generalized case study results and present the contribution of the research and proposes topics for further research.

2 Conceptual framework

In this chapter, I will present the main literature selected regarding demand response and Bitcoin. Some of the information is collected from peer-reviewed academic articles, but a large part is derived from publications and articles written by industry insiders, both from the energy and Bitcoin sphere. There exist a magnitude of peer-reviewed academic literature on demand response, but when it comes to Bitcoin and bitcoin mining in particular, findings of high-quality peer-reviewed academic articles are limited, although a few exist. In addition, the bitcoin mining industry is rapidly changing, so data and research quickly becomes obsolete. Therefore, in analyzing the field, freshness of research material needs to be the top priority.

The phenomenon studied in this master's thesis is Bitcoin mining as a demand response. The literature on bitcoin mining as a demand response is very limited. Therefore this chapter is divided in two parts. First, an explanation of demand response and a framework for assessing different processes for usage as demand response is provided. Then, a brief explanation of how bitcoin works is given. This explanation is divided between Bitcoin as the payment network and bitcoin as the currency, and more specifically how the bitcoin mining process works. This explanation is somewhat simplified, since deeply understanding all the details of how bitcoin mining works is not considered necessary to understand bitcoin mining's potential role as a demand response in an electric power system.

2.1 Demand response

Electricity's main difference from other commodities is that it must be consumed just moments after it is produced (Statnett, 2018). This means that there has to be infrastructure in place to balance supply and demand in real time. This balancing infrastructure can be the supply side in the form of flexible generators who adjust their production up and down depending on the current demand; energy storage in the form of electric batteries, pumped hydroelectric storage or hydrogen; transmission lines expending the geographical size of the market; or the demand side in the form of consumers who voluntarily reduce their electricity usage if needed. The latter is called demand response, and it increases the demand-side flexibility of the system. Fernández & Taibi, 2019, p. 7 defines demand-side flexibility as:

«A part of the demand, including that coming from the electrification of other energy sectors, that could be reduced, increased or shifted in a specific period of time to: 1) facilitate integration of variable renewable energy (VRE) by reshaping load profiles to match VRE generation, 2) reduce peak load and seasonality and 3) reduce production costs by shifting the load from periods with high price of supply to periods with lower prices.»

Since the real-time price elasticity of electricity is very low, especially for residential consumers (Lijesen, 2007), price signals alone have a limited effect in reducing the peak demand. Instead, an electric utility can identify big consumers who voluntarily agree to reduce their electricity consumption during periods of high negative

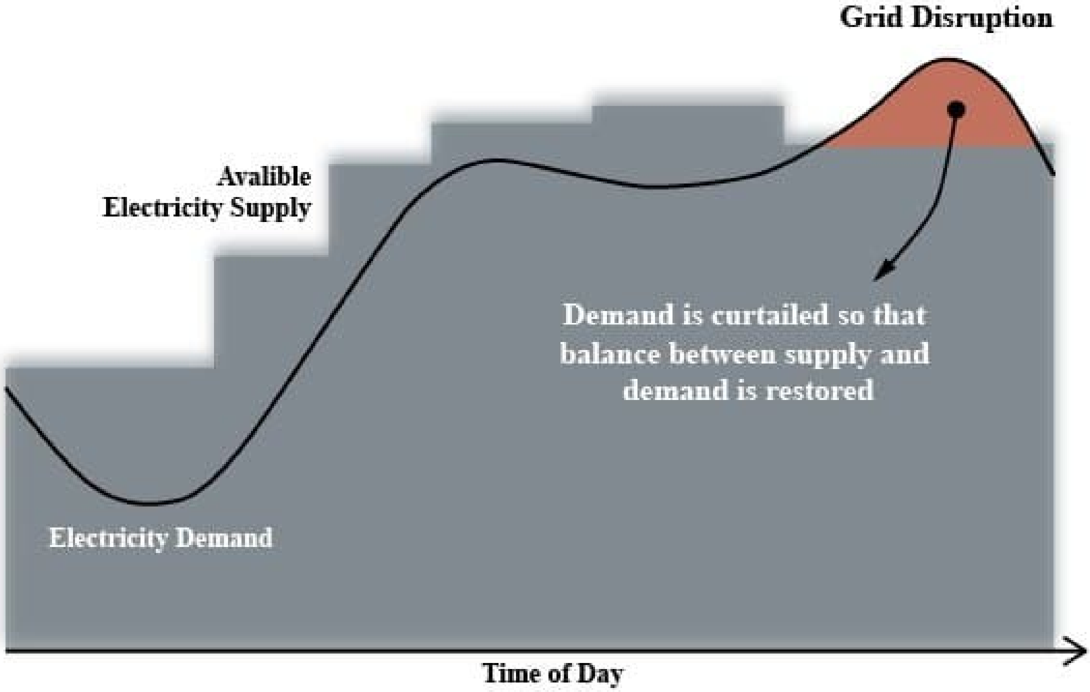
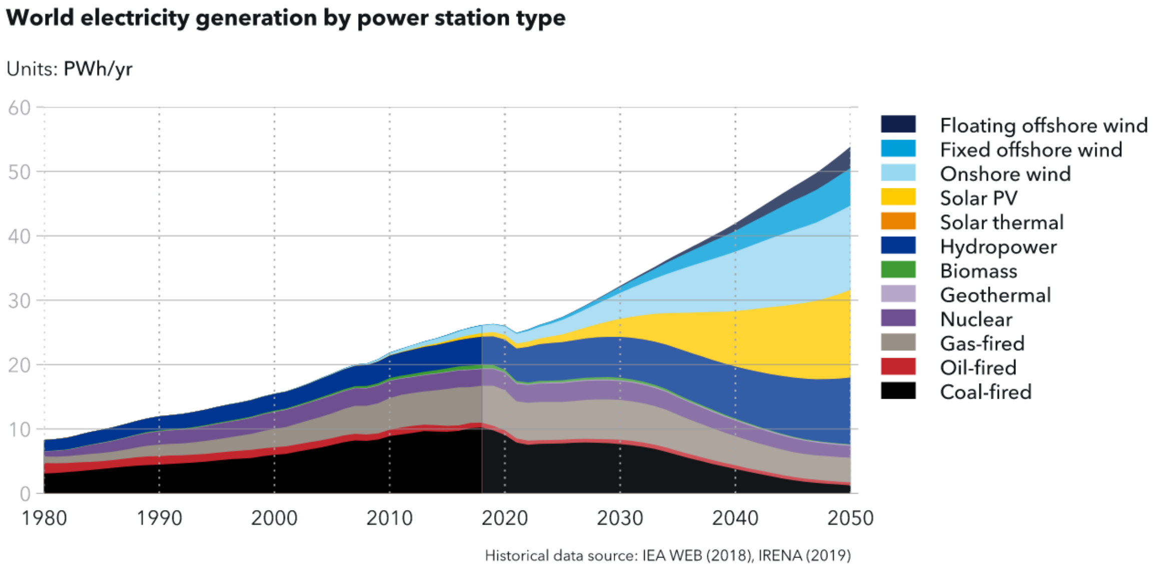


Figure 1: Demand response.

imbalances between supply and demand, in return of a premium. This way, an electric power system can restore system balance without deploying extra generation. The consumer has a power purchase agreement with the electric utility, but sells the utility an option to reduce its electricity consumption in certain situations when the demand exceeds the supply. Demand response can also be done without a power purchase agreement, by voluntarily reducing power consumption during times of high prices.

2.1.1 Why demand response is needed

Fernández & Taibi (2019, p. 8) estimate that to meet the goals of the Paris Agreement, the share of renewable energy in the global annual electricity generation must increase from 25% in 2019 to 86% in 2050. They also predict that from this 86%, about 70% will come from variable sources, which means that variable sources in 2050 will account for around 60% of global annual electricity generation, against 10% in 2020 (Ember, 2020). Variable renewable energy sources only produce electricity when the weather conditions allow for it, but unfortunately, the weather does not consider the current demand for electricity before deciding to turn up as sun or wind. In addition, even the best weather



Historical data source: IEA WEB (2018), IRENA (2019)

Figure 2: World electricity generation by power station type (DNV, 2020).

forecasting models are prone to occasional errors. Because of these characteristics of variable renewable energy, a growth in its share in the electricity mix reduces the supply side's predictability and flexibility, and pushes these responsibilities over on the demand side.

Energy storage technologies like electric batteries or hydrogen offer some of the same advantages as demand response, but the technologies are far from mature and very expensive to deploy. Transmission lines require huge initial investments, as well as introducing a non-negligible electricity loss when electricity is transported across vast distances (Jiménez, Serebsky & Mercado, 2014), especially considering the remote nature of the best renewable energy generation locations. Although we need a mix of all these flexibility solutions, the demand-side stands out from the others when it comes to cost and simplicity. As Shore et al. (2016) explains, power-consuming processes that can be curtailed to release electricity back to the grid are already up and running, and provide flexibility cheaper than other alternatives like storage or backup plants. In addition, as illustrated in figure 3, demand response is very suitable for balancing unpredictable fast changes, while hydrogen specializes in seasonal demand flexibility.

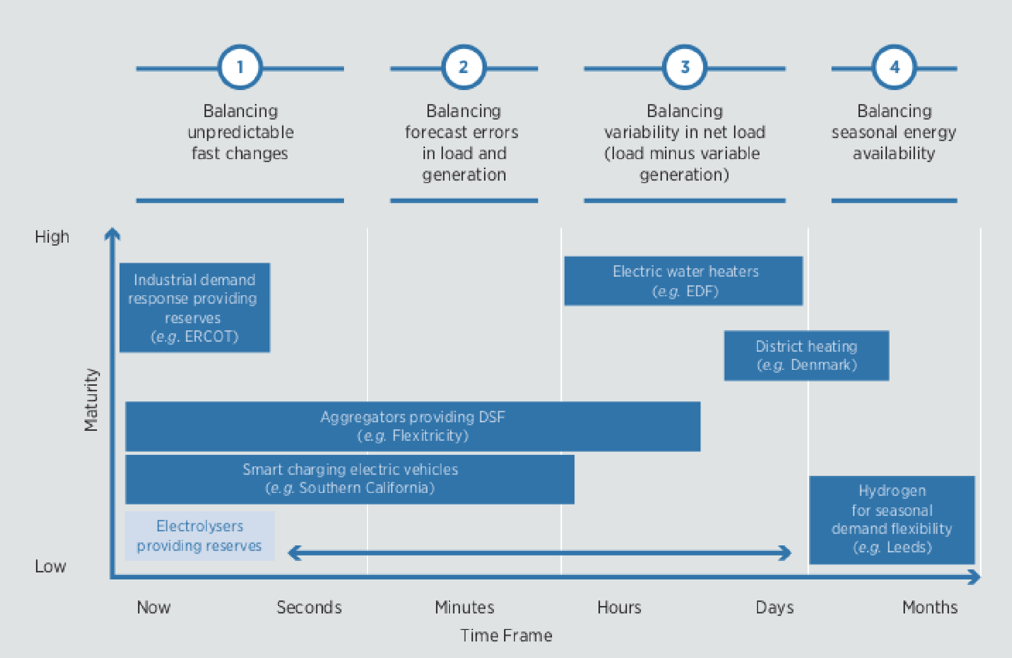


Figure 3: Demand-side flexibility real applications classified by technological maturity and flexibility time scale (Fernández & Taibi, 2019)

2.1.2 Technologies currently used

Fernández & Taibi (2019, p. 10-11), shows that examples of demand response technologies currently used include sector coupling (power-to-gas, power-to-heat, and electric vehicles smart charging) as well as smart appliances in both commercial and residential buildings and industrial demand response. Another example they provide is the load shedding schemes that many European countries have in place that encourage large electricity consumers, like industrial companies, to shed load if required by the system. The Spanish interruptibility service and the German interruptible loads are examples of this approach. In the United States, interruptibility services have existed since the early 1970s, and since the beginning of the 2000s many independent system operators have implemented demand response programs, for example the Electric Reliability Council of Texas (ERCOT) (Fernández & Taibi, 2019, p. 10-11). The focus of this thesis are on these types of demand response programs and interruptibility services, where the ERCOT programs are described more into detail in chapter 4.

The reserve margin in an electric power system is the expected maximum available supply minus the expected peak demand, and is a measurement widely used by electric utilities for maintaining reliability (EIA, 2012). The goal of demand response programs is to financially incentivize heavy consumers of electricity to shift their load from periods of a low reserve margin to periods of a high reserve margin. Especially heavy industry have processes that require huge amounts of electricity, and these could provide flexibility by load shifting if needed. In addition to bitcoin miners (PR Newswire, 2020), examples of such processes include cement production, electric arc furnaces for steel production, aluminum production, and wood pulp production (Shoreh et al., 2016). Being part of a demand response program, an industrial company is not merely a customer of electricity, but can also sell it back to the grid when needed upon a signal from the grid manager. For example, if a steel manufacturer draws 20 MW in full production and stops manufacturing, 20 MW is released to the grid and can be consumed by other consumers who have lower elasticity of demand. This requires that the steel manufacturer is compensated for its losses for stopping production plus paid a premium.

The steel manufacturer gets a new revenue source from the premium it is paid for effectively functioning as an insurance underwriter for the grid system, while the grid manager enjoys a more stable energy system where it knows that it can depend on the steel manufacturer to shut down its operations in a case where the demand is higher than the supply.

2.1.3 Power consumption characteristics enabling demand response

In order to explore the potentiality of utilizing the process of bitcoin mining as a demand response, as we will do in the chapters 5, 6 and 7, a framework for assessing what power consumption characteristics such a process should have is needed. We will go through each individual factor one after another, and as you will understand, all of these factors are related to the flexibility of a process' electricity consumption. These factors have been chosen based on literature about demand response and conversations with experts on the topic. I have chosen to name the framework "Demand Response Flexibility Factors", and I hope it can be used to assess and compare other processes against each other, not only bitcoin mining. Generally, the more flexibility a process has in regards to its electricity consumption, the more technically suitable it is as demand response. A high suitability as a demand response means that the process with great reliability can help stabilize the grid in many different scenarios. Naturally, the more helpful a process is as a demand response, the more it can get paid by being part of a demand response program. Some of these factors are requirements, while others merely serve as advantages. The factors are: Energy intensity; reaction time; availability, cost of reacting; consumption level granularity; and geographic flexibility. Now we will go through the factors with descriptions of what they mean and why they are important. The factors are here ranked by importance, where good scores on energy intensity and reaction time are deemed as requirements, while good scores on the other factors are advantages. The Demand Response Flexibility Factors are:

Energy intensity

The task of demand response is for a consumer to reduce its electricity consumption in certain situations, so that other, less flexible consumers can instead enjoy the released electricity. In order for the released electricity to make a difference for the grid, the released electricity must be of a meaningful amount. EnelX (2020) states that a process should at least be able to reduce 100 kilowatts of electricity in order to be a good candidate for demand response.

Reaction time

Heffron et al. (2020, p. 5) explains that: *“The demand-side must be (technically) enabled to increase or decrease its energy consumption at short notice”*. The reason why the demand response must be able to react quickly is because the imbalances between supply and demand, which it is engaged to stabilize, are often short-lived and hard to predict.

Availability

Availability relates to the up-time of the demand response. If a process is continuously running at full capacity, it will always be able to sell its electricity back to the grid. As will be explained later, many demand response programs work by letting the demand response resource sell its capacity in various day-ahead markets. A requirement for being able to sell the capacity in the day-ahead markets is that the demand response resource must consume electricity at minimum the level of the sold capacity for the time it sold it. In other words, since the demand response resource has sold its capacity, it must make sure that this capacity is available to curtail when needed. This makes availability an extremely important power consumption factor for processes utilized as demand response. The more stable a load is, the more availability it has, and the better suited it is for usage as demand response.

Cost of reacting

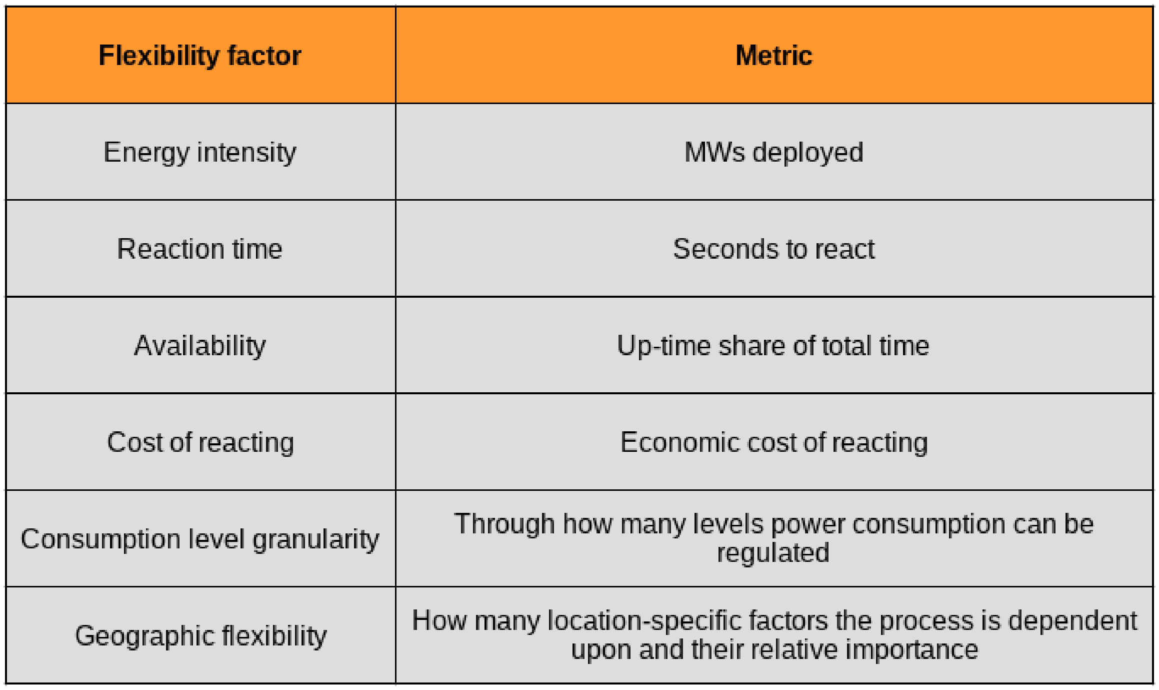
A company will only reduce its electricity consumption if it is financially beneficial for them to do so. In other words, the payments for reducing electricity consumption must be higher than their cost of reacting. Therefore, a high cost of reacting effectively limits the possibilities for when a process can participate in load shedding as part of a demand response program. Shore et al. (2016) explains that most industries have difficulties in reducing production levels fast because of constraints regarding their customers' needs and interdependence of various internal and external processes and that generally the best industrial applications of demand response are operations that are based on a single source of demand.

Consumption level granularity

A process where it is possible to adjust the production and electricity consumption in a granular way is preferable to a process where you only have two choices; either to consume at full capacity or shut the process down entirely. This is because a process that can turn its energy consumption up and down through many levels can sell many different amounts of electricity back to the market, instead of being limited to just one amount. In some cases, the grid is in need of a specific amount of electricity to stabilize its frequency (Hayden, 2020).

Geographic flexibility

Demand response is about providing flexibility to local electric power systems, so if processes are able to locate themselves almost anywhere, they can be used for demand response in many different electric power systems. To put it simply, the demand response resource must seek out the electric power system in need of demand response. In addition, many of the regions with the highest demand for these solutions are located in high variable renewable energy clusters far away from population centers. Most industries are relatively inflexible when it comes to where to locate their processes. Examples of sources of such inflexibility can be access to manpower, raw materials and logistics networks for their finished products.



Flexibility factor	Metric
Energy intensity	MWs deployed
Reaction time	Seconds to react
Availability	Up-time share of total time
Cost of reacting	Economic cost of reacting
Consumption level granularity	Through how many levels power consumption can be regulated
Geographic flexibility	How many location-specific factors the process is dependent upon and their relative importance

Table 1: Demand response flexibility factors.

2.2 Bitcoin Mining

To understand Bitcoin mining's potential role as a demand response in the electric power system, it is vital to understand what its purpose is and have a minimum of knowledge regarding how it works. To put it simply, Bitcoin is a payment network secured by bitcoin miners. We will start with the history and motivation of Bitcoin's creation, followed by a description of how Bitcoin works in practice and how bitcoin miners are playing the fundamental role in securing the network.

2.2.1 Bitcoin's History and Purpose

The Bitcoin Project (2021) defines Bitcoin as: *"A **consensus network** that enables a new **payment system** and a completely **digital money**. It is the first **decentralized peer-to-peer payment network** that is powered by its users with **no central authority or middlemen**."* From this definition, it follows that Bitcoin is both a payment network as well as the native money of this payment network. In this thesis "Bitcoin", with the first letter capitalized, refers to the payment network, while the non-capitalized "bitcoin" refers to the native money of this payment network.

In October 2008, an individual or group operating under the pseudonym Satoshi Nakamoto posted a link to a research paper titled «*Bitcoin: A Peer-to-Peer Electronic Cash System*» to a mailing list consisting of cryptography enthusiasts from all over the world (Finley, 2018). This paper explained in great detail how to implement a secure system for electronic transactions without relying on trust (Nakamoto, 2008). A core of the cryptographers from this mailing lists then started to cooperate across multiple jurisdictions to create the Bitcoin network based on the findings of this research paper. The Bitcoin network finally emerged on January 3. 2009, when the first block was mined by Satoshi Nakamoto (Redman, 2020). In Bitcoin transactions it is possible to embed a custom message (Yampolskiy, Sleiman, & Lauf, 2015), and the first block of the network contained the following message: *"The Times 03/Jan/2009 Chancellor on brink of second bailout for banks"*(Davis, 2011). The message on the first block and online posts and emails by its creators (Satoshi Nakamoto Institute, 2021), in addition to the fact that Bitcoin was created during the financial crisis of 2008 (Noogin, 2018), indicate that the payment system was created as a response to the banks' and governments' conduct in the time before and around the financial crisis of 2008.

Bitcoin is the first payment system powered by its users with no need for a central authority or middlemen. As Jenssen (2014, p. 16) explains, trusted third parties, such as banks, are required to operate traditional payment systems. The underlying reason for this is that all value exchanges between people until now have required at least some degree of trust in one another. If people have not yet, or been able to, establish trust between each other, a trusted third party is required to facilitate value exchanges and protect private property rights. The weakness of a trusted third party system is that it does not remove the need for trust, but merely transfers it to third parties that people have no other choice but to trust. Examples of such third parties include banks and governments. Gur (2015) found a relationship between the level of trust between citizens and the financial development of nations. Based on his findings, we can view the need for trust as an economic cost. Bitcoin seeks to eliminate the need for trusted third parties, and the miners play an essential role in the infrastructure, as will be explained in chapter 2.2.2.

The Bitcoin protocol is the rule-set of the Bitcoin network, and is open source and available to anyone through the internet. One of the most important of the rules is the maximum supply limit, which indirectly states that it will never be created more than 21,000,000 Bitcoins (Bitcoin Wiki, 2020, Protocol rules). The maximum supply limit is estimated to be reached around year 2140 (Hayes, 2021). The minting of new bitcoins is also following a strict schedule for how many new coins should be produced in a given time-span. These strict rules and planned schedules of bitcoin minting stays in stark contrast to the way fiat currencies are managed, where central banks have no limits in how much they can increase the money supply in a given time-span (US Debt Clock, 2021). For example, in 2020 alone, after heavy quantitative easing during the Covid-19 pandemic, the U.S. Dollar M2 money stock increased by around 24% (St. Louis FED, 2021). In the same year, the Bitcoin supply increased by a meager 2.4% (Blockchain.com, 2021). Bitcoin's inflation rate is also following an exponentially decreasing function, meaning that the inflation rate will decrease over time (Bitcoin Wiki, 2020, Controlled supply). Other examples of protocol rules include how many transactions each block can include, and how long average time it should be between blocks. The Bitcoin protocol is governed by the miners and nodes, who collectively decide which rules to follow (Galea, 2018).

The stable and limiting protocol rules, and the fact that everyone in the network are forced to follow them, supports the thesis of bitcoin as a good long-term store of value. Over thousands of years, precious metals like gold and silver have been the most used vehicles for preserving purchasing power over long periods of time. The strongest narrative for bitcoin these days is “digital gold” (Forbes, 2020). Since bitcoin is not controlled by a centralized entity and cannot be inflated by a central bank or other malicious actors, it fulfills some of the same economic properties as gold, as outlined by Bull Jenssen (2014). Bitcoin has during the latest months seen an explosion in institutional demand, many of them investing in it on basis of the digital gold thesis, for example the business intelligence company Microstrategy (MicroStrategy, 2020).

Merely serving as a digital alternative to gold is one of the potential futures for Bitcoin. Another potential future that also aligns with the digital gold thesis is for Bitcoin to serve as the base layer of a whole new monetary system. Bathia (2018) explains how gold, before Modern Monetary Theory was introduced, served the role as a payment system. Not only through the exchange of physical gold, but through gold certificates. This is known as a layered payment system, where the physical gold serve as the base layer and the gold certificates serve as the second layer. The important thing here is that the gold certificates, which are used for day-to-day purchases, were backed by and could be redeemed for physical gold. Bathia (2018) further explains that Bitcoin could fulfill the same role as gold historically has done by being the base layer in a money system, while having more layers on top of it where day-to-day transactions are handled instantly outside the blockchain. An example of a such a second layer for Bitcoin is the Lightning Network (Lightning Network, 2021).

2.2.2 How Bitcoin works and the role of bitcoin miners

Bitcoin is a complicated technology, and a detailed explanation of how it works is beyond the scope of this master’s thesis. Therefore, this section is somewhat simplified, and I encourage the reader to check out resources from the Bitcoin Project to learn more (Bitcoin Project, 2021; Resources).

Together with cryptography, the main technology powering Bitcoin is blockchain. A blockchain is a specific type of database that stores data in blocks that are chained after each other by cryptographic relationships (Conway, 2020). In the case of Bitcoin, the blocks consist of transactions. The blocks are chained chronologically after each other, which means that the last block in the chain always is the newest one produced. Bitcoin's blockchain is distributed in computers all over the world (Majaski, 2020), and all account balances and transactions are available for anyone to verify (Blockchain.com, 2021; Explorer). Each new block in the chain has a cryptographic relationship to the previous block in the chain, which ultimately links all the blocks together. This means that if someone goes back in the blockchain and tries to change an earlier transaction, it will break this relationship and render all the following transactions in the blockchain invalid.

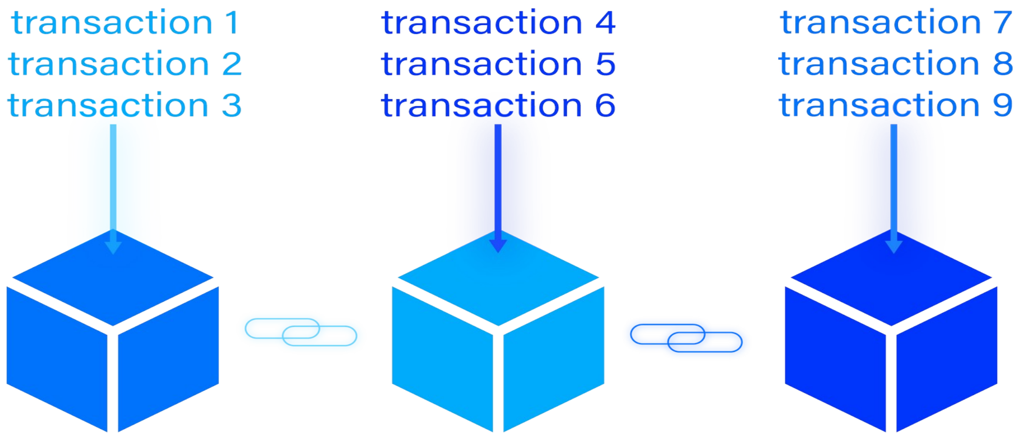
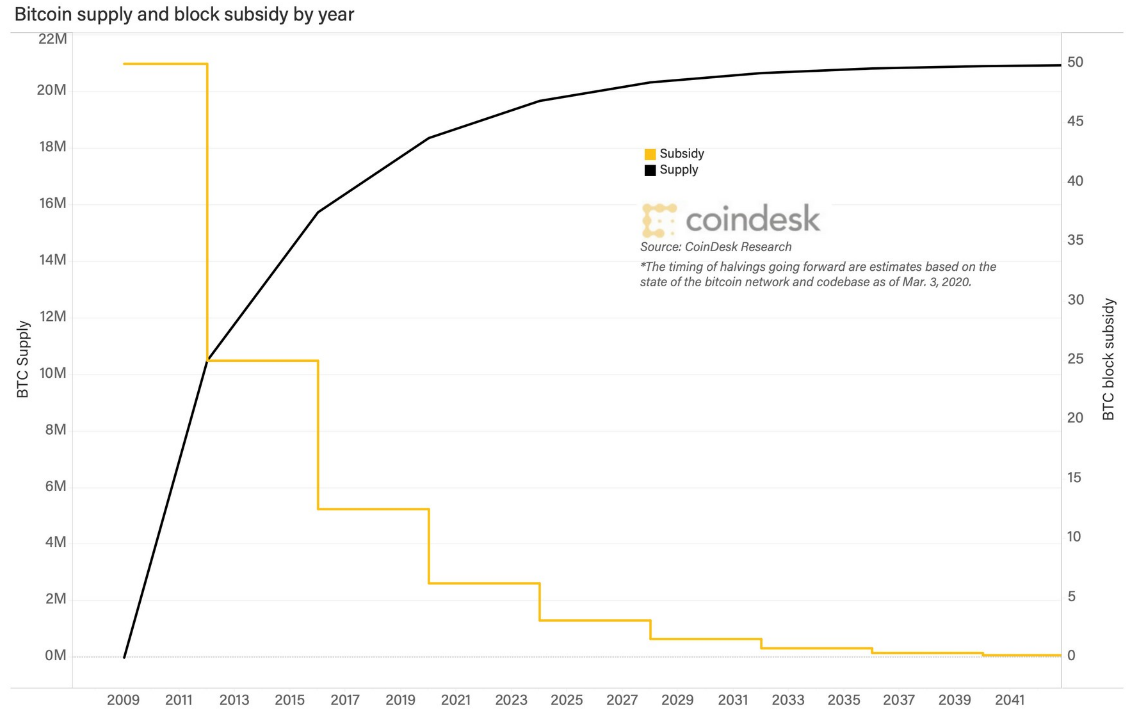


Figure 4: The blockchain.

Bitcoin miners are computers distributed all over the world competing with each other in creating the next block in the Bitcoin blockchain. The way it works is that miners fill their blocks with unconfirmed transactions and start to compete in solving a cryptographic puzzle, and the first miner to solve it is allowed to add their newly created block to the blockchain. When this block is added to the blockchain by the miner, the transactions in this block are converted from unconfirmed to confirmed, and the miner who solved the puzzle receives a block reward. The block reward, together with the transaction costs provided by the users, is the payment to the miner for solving the puzzle and creating the block. The block reward constitutes the Bitcoin inflation, and decreases with 50% for every 210,000 blocks produced. The block reward was initially 50 Bitcoins, but is currently 6.25 Bitcoins (Coin Market Cap, 2021), and will decrease to 3.125 Bitcoins in 2024 (CMC Markets, 2020). The average time between the blocks in the Bitcoin network is 10 minutes. For the miners, it means that every 10 minutes on average, they compete with each other to get 6.25 Bitcoins plus the transaction fees in reward.



Source: CoinDesk Research

*The timing of halvings going forward are estimates based on the state of the bitcoin network and codebase as of Mar. 3, 2020.

Figure 5: Bitcoin supply and block reward by year (Hertig, 2020).

In addition to confirming transactions and adding new coins into circulation, the most important role of Bitcoin miners is to secure the network. The point of the proof-of-work algorithm is to make it economically expensive to attack the system. When a new and valid block is found by a miner, all other miners immediately start to solve for the next block in order to put it on top of the previous one. An attack on the network requires over 50% of the total computing power for a sustained period of time, and is called a 51% attack. A 51% attack is considered extremely unrealistic, since you: a) must have over 51% of the computing power; and b) must run this enormous amount of computing power for a sustained time, giving you extreme electricity costs. Bitcoin is often critizised for its huge electricity consumption, but it is important to realize that this is a feature and not a bug. The electricity secures the network and backs its native money by making it extremely costly to attack the network.

Bitcoin mining is effectively a number-guessing game where the first miner to guess the correct number creates the new block and is rewarded with Bitcoins from the block reward and the transaction fees. To keep the minting of new bitcoin stable, the difficulty in Bitcoin mining is adjusted every 2016 blocks, and set so that it should be 10 minutes between each block on average. This means that if a lot of new Bitcoin miners join the market, the difficulty will increase, and opposite if a lot of miners leave the market. Without the difficulty adjustment, the average time between each block would decrease when new miners joined the market. The reason for this is that when new miners join the market, the total computing power in the network increases and thus also the total probability of solving the cryptographic puzzle. The difficulty adjustment is one of the Bitcoin protocol rules, which means that the average of 10 minutes between blocks is set in stone. With this also follows the very important realization that the number of new Bitcoins minted long-term has nothing to do with the total computation power in the network, but follows a stable and planned schedule over time. This is one of the ways in which Bitcoin mining differences from gold mining. An increase in the gold price means a higher profitability of gold mining, leading to an increase of gold mining activities. So far the same as for Bitcoin. The difference lies in the fact that while the increase of gold mining activities leads to an increase in new gold supply, the total amount of bitcoins mined has nothing to do with the level of mining activities, since the difficulty of mining increases with Bitcoin mining activity. This means that the new supply of Bitcoin will always follow the planned schedule, no matter how great or small the mining activity is. In other words, Bitcoin has a completely fixed supply.

2.3 Summary of chapter

In this chapter, the concepts of demand response and bitcoin mining were illuminated. From the literature about demand response, I characterized Bitcoin mining as a potential demand response system. I also presented a framework for evaluating industries' technical potentiality as such systems, which later will be used to determine bitcoin mining's potential role as a demand response.

In order to further analyze Bitcoin mining in this context it is important to posses a basic knowledge about Bitcoin and especially bitcoin mining. Therefore, I presented a short introduction to Bitcoin and its most important characteristics, what bitcoin mining is and how it is done. The bitcoin miners' role in the energy industry as heavy and flexible consumers of electricity participating in demand response will be closer described in chapter 4, 5, 6 and 7.

3 Methodology

In this chapter, I will describe the research design that was chosen for this study. I also give an explanation of the data collection methods to shed light on all the data sources used, both the qualitative and the quantitative. In the end, any limitations of the research is investigated based on the judgments of validity and reliability.

3.1 Research question

As already presented in the introduction, the research question is:

"What are the enabling and constraining factors for utilizing Bitcoin mining as a demand response in an electric power system?"

I will employ a sample strategy called critical case sampling in order to narrow down the variation so that the focus can be placed on similarities instead. It is this focus on similarities Flyvbjerg (2011) had in mind when he wrote *"If this is valid for this case, then it applies to all cases"*. Based on his methodology, the research question will be answered through the case study of Bitcoin mining as a demand response in the ERCOT-system in Texas. In order to answer this research question, we must have a framework of assessing a demand response.

In chapter 2, I proposed a framework with distinctive characteristics for assessing a process' suitability as demand response. This framework will be used on bitcoin mining in order to answer the research question. My framework includes the following factors: energy intensity, reaction time, availability, cost of reacting, consumption level granularity and geographic flexibility. I will assess Bitcoin mining's suitability as a demand response by these factors, based on the information I found from the case study of Bitcoin mining as a demand response in Texas. Moreover, in order to answer the research question, not only the technical factors must be assessed, although they are the most important for a demand response. A study that assesses bitcoin mining as a demand response based only on technical factors will lack important dimensions, since bitcoin mining is a new industry with many important elements to consider aside from the pure technical. Therefore, to add more depth to my analysis, I will also assess various economical, political and environmental factors of bitcoin mining that can have influence over its suitability as a demand response. All the factors can together be summed up as a simplified PESTEL-analysis. As defined by CFI (2021), *"PESTEL Analysis is a strategic framework used to evaluate the external environment of a business by breaking down the opportunities and risks into* ***P****olitical,* ***E****conomic,* ***S****ocial,* ***T****echnological,* ***E****nvironmental and* ***L****egal factors"*. I have simplified the framework by removing the social and legal factors, as they are similar to the political factors in nature and will thus be analyzed there. Also, the framework is originally intended for evaluating the external environment of a business or industry, but I will use it both for internal and for external factors. To sum up, the simplified PESTEL-framework is used because it allows for analyzing Bitcoin mining's suitability as a demand response from several perspectives.

3.2 Research design

Selltiz, Wrightsman and Cook (1981) has the following definition of research design:

"Research design is the deliberately planned arrangement of conditions for ***analysis*** *and* ***collection of data*** *in a manner that aims to combine relevance to the research purpose with economy of procedure."*

The two most important factors from this definition are data collection and analysis. The research design is about making decisions in how to go through these procedures in the best possible way, given the study object. My choice of research design is a case study, where I will study Bitcoin Mining as a Demand Response in the ERCOT-system in Texas. A further description about the case will be provided in chapter 4.

"A case study is an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident" (Yin, 2018, p. 13). That is to say that a

case study is suitable in situations where the researcher has an ambition to understand a phenomenon, but the understanding of the phenomenon is tied to important conditions regarding the context. In my case study, bitcoin mining as a demand response is the phenomenon, and ERCOT is the context. I have chosen a case study since bitcoin mining as a demand response is a new phenomenon and as far as I know, ERCOT is the first context it is used within. Therefore, not many other sources other than this exists and to get as much valuable information as possible about the phenomenon, an investigation of the phenomenon within the context is needed.

3.2.1 Data collection

A case study can be based on both qualitative or quantitative data, according to Yin (1994). The thesis is based on both, but I have constructed my thesis using qualitative data collection. Qualitative research methods aims to discover what individuals feel or think about a phenomenon, as well as finding the motives for their actions. In other words: *“The qualitative interview is especially suited for accessing the experiences, thoughts and feelings of an informant”* (Translated from Dalen, 2011, p. 13). An additional attribute of qualitative research is a smaller group of respondents, as well as putting more responsibilities on the scientist himself for data analysis than in quantitative research. In quantitative research, the data speaks for itself, but in qualitative research, the scientist is a middleman with responsibilities in interpreting the data. Both quantitative and qualitative data are collected through interviews and from ERCOT reports. Several interviews with industry insiders have been done. The interviews have given me access to data not found online as well as pointing me in the direction of what data is relevant and where I can find it.

The aim of this thesis is to understand and describe the enabling and constraining factors in utilizing bitcoin mining as a demand response in an electric power system. I am not looking for any clear cause and effect relationships here, as is the goal of most quantitative surveys, and there potentially exists a magnitude of different enabling and constraining factors, which are qualitative in nature. Therefore, I have found a qualitative approach to be appropriate for the study. Nevertheless, it is important to keep in mind that some of the data used in my analysis is quantitative, but it is still analyzed through qualitative methods.

As mentioned, this thesis is a single case study with multiple units of analysis. Miles, Huberman, & Saldaña (2014) explain that examples of different units of analysis include organizations, partnerships, projects and processes. In my case study, the units of analysis are reports from ERCOT and other industry insiders; research papers and other documents related to the Texas electricity system and their use of demand response; as well as transcribed interviews from industry insiders in the bitcoin mining sector in Texas. The challenges in data collection for this research is not about getting data about the ERCOT-system and their use of general demand response technology for grid stabilization, as there exists a magnitude of qualitative and quantitative information readily available on their website. Challenges in data collection present itself in getting specific information about bitcoin miners in Texas and how they are providing demand response services to the market, as there exists limited information about this online, although some data can be found online with the guidance from industry insiders. In order to get access to hard-to-find information and learn more about the topic, I have conducted interviews and informal meetings with various industry insiders to obtain qualitative and quantitative information that is not accessible through the internet. Interview objects here include bitcoin miners in Texas that are participating in demand response themselves, as well as other bitcoin mining specialists from around the globe. The interviews was done using a semi-structured interview guide (Johannessen, Christoffersen & Tufte, 2011), by outlining a few important questions and letting the interviewee explain things freely.

3.2.2 Data analysis

When it comes to analyzing the written documents, I have used a technique called qualitative coding. According to Charmaz (2014), a code is a short phrase or word which summarizes the meanings behind a piece of data, for example a sentence or a statement in the data. When analyzing vast amounts of qualitative data, some kind of coding method is needed, both in order to file and organize the data, but also for the sake of interpreting. Here, interpretation is achieved through linking the data, thus leading the researcher from the data to a greater idea, and back again to the data which underlie this idea (Miles et al., 2014). Based on the suggestions from a renowned expert on coding in qualitative studies, Johnny Saldaña, I have applied a deductive coding approach which means dividing the codes into categories, concepts and themes.

In analyzing the interview data, I both used the deductive coding approach and used the method of meaning condensation. Kvale et al. (2015) describes meaning condensation as a method for simplifying the processing of complex and long texts or interviews, which involves breaking the data material obtained into shorter formulations. First I recorded the interviews and transcribed them. Then I wrote a shorter version of the transcription with only the most important facts obtained in different sentences. Then I organized and analyzed them based on the predefined codes.

3.3 Validity and reliability

Yin (2018) describes validity as a measurement of how accurately a test measures what it is supposed to measure. In a case study, the validity can be increased by including enough perspectives, as well as by asking key informants and advisers to review the case study report and results (Yin, 2018).

Validity can be divided into internal and external validity according to Yin. Internal validity, which also is known as credibility, relates to if the research has come to the right conclusion, while external validity, which also is known as transferability, is related to questions regarding if the results obtained from the study can be generalized (Yin, 2018). This is a highly relevant question for a case study, since the goal of a case study is to study a phenomenon inside its natural context in order to generalize the findings.

Measures taken to improve validity in this case study is among others to provide a detailed case explanation in order for readers to understand the relevance, as well as asking key informants and advisers to review the case study report and results along the way.

When it comes to reliability, as described by Yin (2018), the goal is to maximize the probability of another researcher following the exact same procedures in conducting the same study has the same findings and conclusions. This is largely about minimizing biases and errors in the study. Yin recommends to documenting the study along the way.

The data collected is considered to be reliable, especially the data collected from ERCOT's website. ERCOT is the operator of the electric power grid and the market in Texas, and is dependent on providing the correct information on their website in order to inform all the participants in their market. Both qualitative and quantitative data is collected from ERCOT's website, and especially the quantitative data is considered highly reliable, since this data is mostly related to prices and capacity, which is information that can easily be verified by market participants. When it comes to the data collected through interviews, it is considered reliable since it has been cross-checked by other interview objects. One limitation of my study is that I have not been able to interview people from ERCOT, but only Bitcoin miners.

4 The case of bitcoin mining as a demand response in the ERCOT-system in Texas

This chapter will contain a description of the context and a justification for why it was chosen. The reason why this case study will take advantage of the ERCOT-system in Texas as a context is because the state is at the center of innovation in utilizing bitcoin mining, as well as other demand responses, as ways to stabilize the electricity grid. The electricity market in the ERCOT-system in Texas is unique with its combination of little regulations and cheap prices, as well as its sudden fluctuations in both supply and demand, due to the high degree of variable wind power generation and unpredictable heat waves. As we saw during the winter storm that swept over the state in February 2021, unpredictable freezing weather can also occur, which further increases the need for demand-flexibility. The state is also a hub for energy intensive industry, like oil and gas refining, chemical manufacturing and a growing bitcoin mining sector. Heavy industrial consumers like these are helping to balance the electric power system through participating in demand response programs as well as through voluntary demand response initiatives by simply stopping production when the price spikes in order to save on electricity costs. Even though Texas is currently not among the biggest Bitcoin mining hubs in the world, the growth of new mining operations in the state has recently been immense, and the state is also taking advantage of their bitcoin mining industry as demand response during periods of high load.

The following sub-chapters start with a description of the regulatory structure of Texas' electric power system, where key regulatory traits of the system are identified. Thereafter a description of the characteristics of supply and demand is provided, including the power generation mix, the electricity prices and the fluctuations in supply and demand. In the end of the chapter, an account of the Bitcoin mining industry in Texas is given, and more specifically how this industry relates to the state's energy sector and how it currently acts as demand response.

4.1 The structure of Texas' electric power system

The Texas Interconnection differs from most other American grids in that it is not connected to any other grid in the country (Electricchoice.com, 2020). This makes the state's electricity system independent from federal regulations in most respects (Galbraith, 2011). This freedom with respect to federal regulations lets Texas choose their own regulations for their electric power system, and they chose to deregulate the market in 2002 (Electricchoice.com, 2017). This means that all the resources in the system, from transmission lines to generation units, can be privately owned and operated. A non-profit membership organization exists with the goal of ensuring a reliable grid and efficient electricity markets (ERCOT, 2021; Vision). This organization is called the Electric Reliability Council of Texas (ERCOT) and is an Independent System Operator (ISO), which means that they are responsible for managing the flow of electric power to consumers as well as providing reliability planning for the future (ERCOT, 2021). ERCOT is run by the participants of the electric power system, such as investor-owned

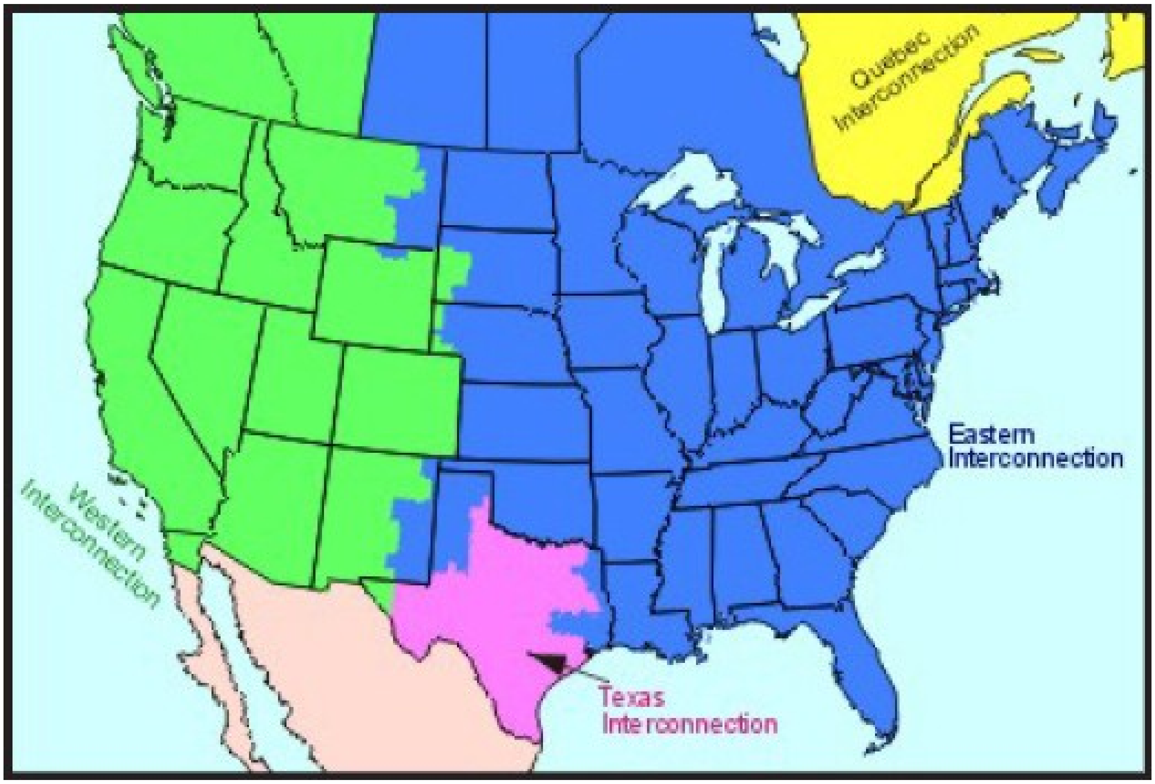


Figure 6: North America's electricity interconnections (NERC, 2011).

electric utilities, municipals, cooperatives, retail electric providers, power marketers, generators and electricity consumers (ERCOT, 2021; Members).

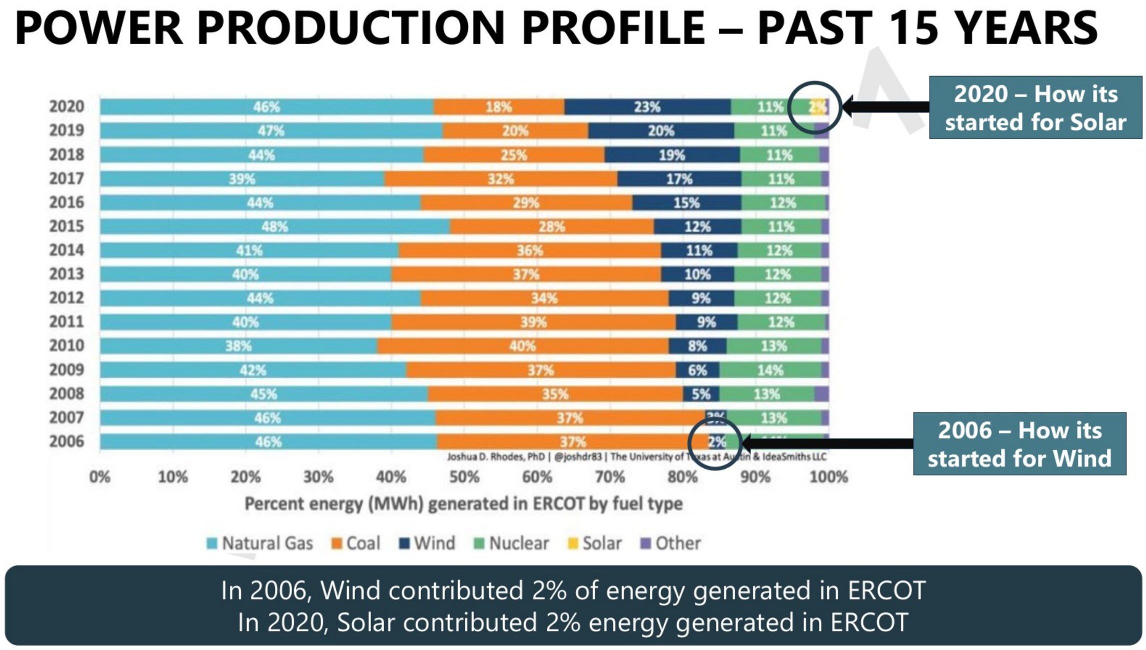
As described by Cameron et al. (2021), around 560 generators compete against each other in generating electricity, and the customers can freely choose between around around 120 retail electric providers, who buy power in bulk from the generators and resell it to the end consumers. The electricity is transported from generators to consumers through transmission lines controlled by around 85 different companies (Cameron et al., 2021). It is an energy only market, which simply means that the generators are paid only for the electricity they generate, not receiving any subsidies for sitting idle with available capacity (Statnett, 2015). The other main alternative in market design is a capacity market. Here, adequate capacity in the electric power system is secured by giving flexible thermal power plants and other providers of flexibility sufficient earnings in another market held outside of the energy market (Statnett, 2015). As Statnett (2015) further explains, in an energy only market like Texas', thermal power plants and other flexibility providers get their earnings from the day-ahead- and balancing markets alone, and the market itself is responsible for balancing the system. Price signals serve as an important stabilization mechanism, and by letting real-time prices spike up to more than $9,000 per MWh during the hottest periods of the year, ERCOT aims to incentivize some of its flexible power plants to stay idle and save capacity until the periods of the year when consumers need this capacity the most and thus are willing to pay the most for it. These extreme price spikes also incentivize consumers to act as demand responses, either through participating in ERCOT's demand response programs where they have a power purchase agreement and can sell their electricity back to the grid during high load times, or simply by voluntarily decreasing their power consumption during price spikes in order to save on their electricity costs. These two main ways of providing demand response will be described more in detail in the end of the chapter.

4.2 Supply and demand characteristics

Texas is known as an energy powerhouse, both when it comes to oil and gas, but also electricity. Texas produces more electricity than any other state in the US, generating almost twice as much as Florida, the second highest producing state (EIA, 2020, Texas). Since the state exports minimal amounts of electricity, it is naturally also the biggest consumer in the US. As we will learn later in this section, in addition to being characterized by its high electricity production and consumption, Texas is also known for its high share of wind in the power generation mix and its high growth in solar power deployment, as well as for having high fluctuations in the electricity demand due to extreme weather.

4.2.1 Power generation mix

ERCOT expects to have access to over 86 gigawatts of capacity during the summer 2021 peak demand, where 53% comes from natural gas, 23% from wind, 15% from coal, 5% from nuclear and 2% from solar (ERCOT, 2021, Fact sheet). When it comes to generation, natural gas is responsible for 46%, wind for 23%, coal for 18%, nuclear for 11% and solar for 2% (Lancium, 2021; Figure). Minton (2020) explains how the fuel mix of Texas' has changed during the past decade. In 2009, coal was the source of almost 37 percent of Texas' electricity while wind only provided around 6 percent. Since then, three coal plants have closed down and the wind power generation has more than quadrupled. Because of the enormous growth in wind power, Texas is the leading state in the United States both in installed and under construction wind capacity (AWEA, 2020), and only four countries world-wide have more installed capacity. Most of the wind power capacity is located in the remote and vast territories of the western part of the state, where there is plenty of wind and access to cheap land.



POWER PRODUCTION PROFILE – PAST 15 YEARS

2020 – How its started for Solar

2006 – How its started for Wind

Joshua D. Rhodes, PhD | @joshdr83 | The University of Texas at Austin & IdeaSmiths LLC

In 2006, Wind contributed 2% of energy generated in ERCOT
In 2020, Solar contributed 2% energy generated in ERCOT

Figure 7: Power production in Texas over the past 15 years (Lancium, 2021).

Not only is Texas rich on wind, but also on sun, and according to EIA (2021), 28% of the new utility-scale solar PV capacity in the United States in 2021 is planned in Texas, giving them around 4 gigawatts of new solar this year. In common with the state’s wind resources, the solar resources are located in the deserted areas in the west, far away from where the population is clustered in the eastern part. This means that the growing share of remotely generated wind and solar in the energy mix is increasing the need for long distance transmission lines to transport the electricity across the state, which are yet to be developed. This is illustrated in figure 8.

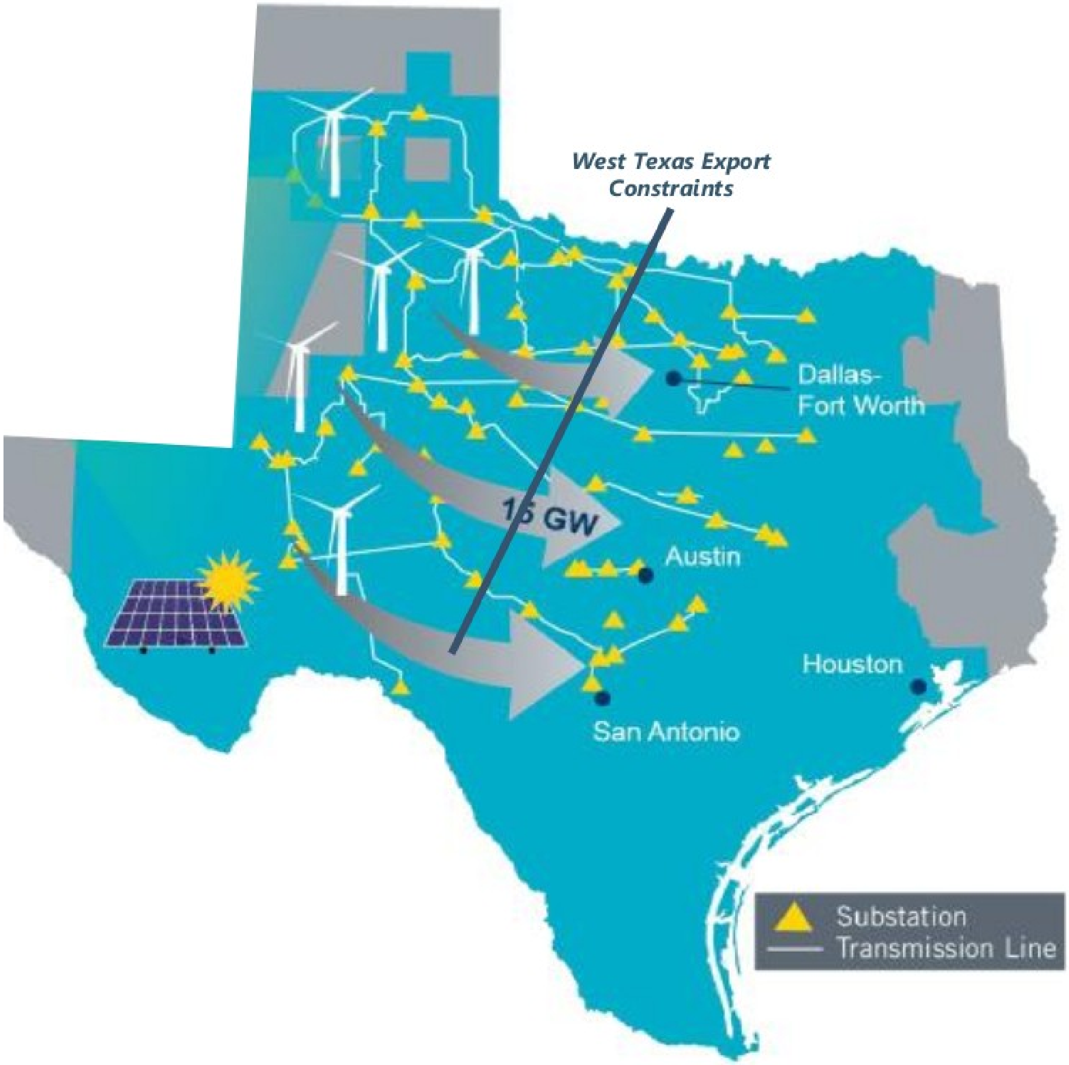
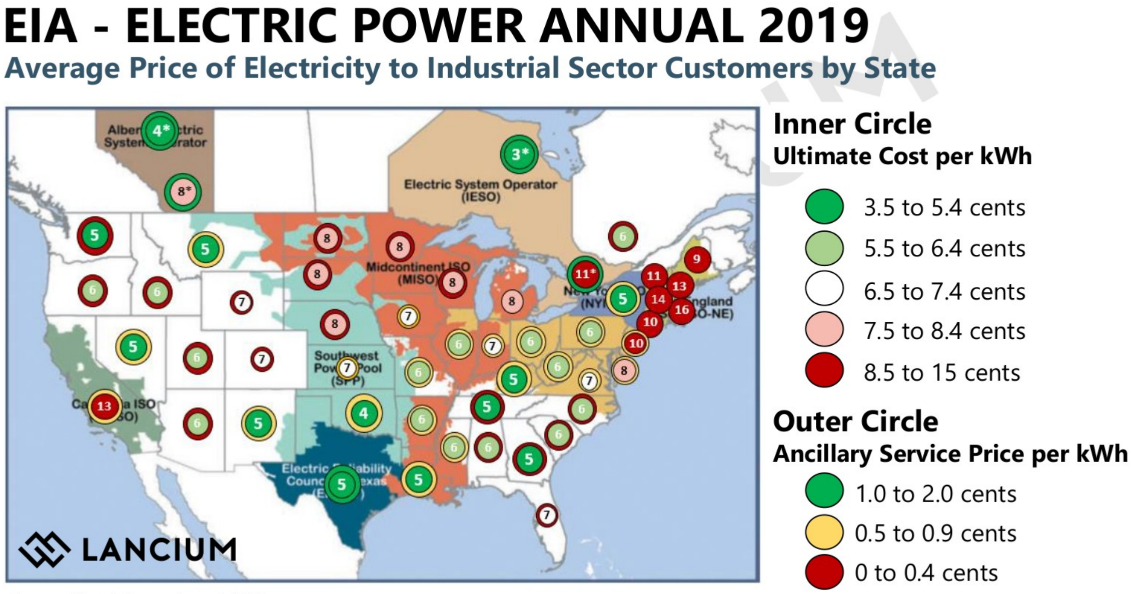


Figure 8: Wind and solar energy export constraints in Texas (Lancium, 2021).

4.2.2 Electricity prices

Texas has abundant energy resources, and the electricity in the state is among the cheapest in the United States. This is especially true for the industrial consumers, who enjoy an average electricity price that is about 23% less than the average in the United States (EIA, 2020; Texas). Texas' average industrial electricity rate in 2019 was $5.25 per MWh, compared to for example California's $11.43 (Waterpedia, 2019). The cheap electricity rates have attracted a huge industrial sector, who accounts for more than half of the state’s energy consumption (EIA, 2020, Texas).



Source: Electric Power Annual 2019

Figure 9: Average price of electricity to industrial sector customers by state in 2019 (Lancium, 2021)

In addition to being low, the prices in Texas are characterized by huge volatility, where prices can spike as high as $9000 per MWh during the hottest periods of the summer. Short periods of negative prices is not unusual either in times of high wind generation combined with very low demand as seen in figure 10. The reason behind these price-swings is volatility in demand and available supply because of a high share of wind power. This means that the prices for ancillary services, which are the balancing services provided by the demand response resources, are very high in Texas, as seen in figure 9. The combination of low power prices and high prices for ancillary services makes Texas a very attractive location for bitcoin miners.

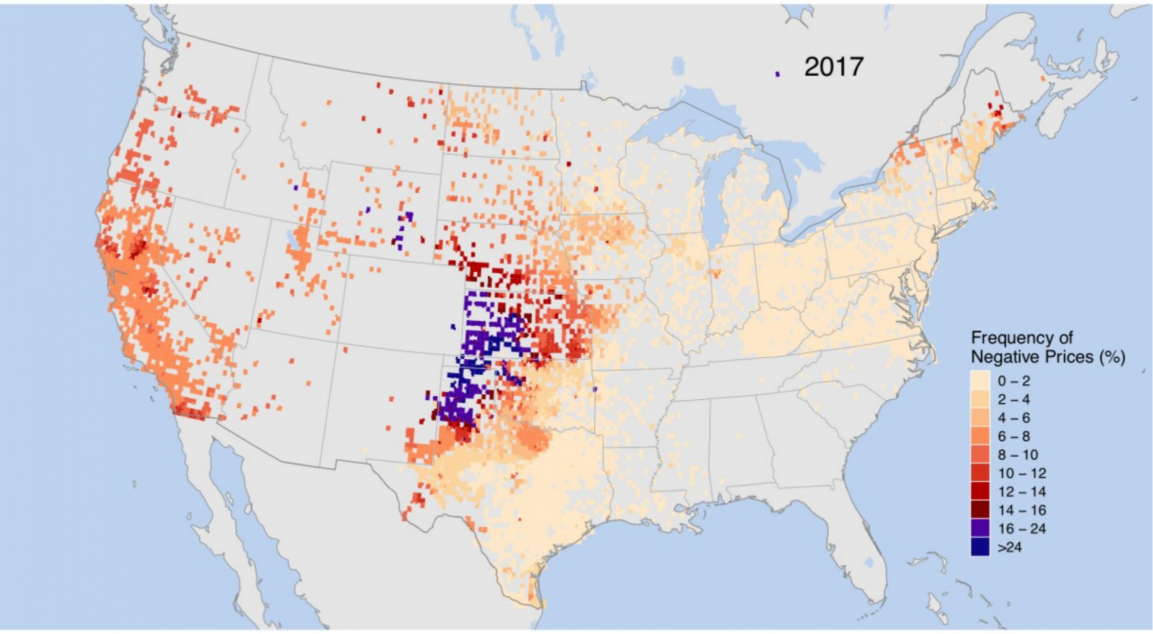


Figure 10: Frequency of negative locational marginal prices, or real-time power prices, in 2017 (U.S. Department of Energy, 2020).

4.2.3 Fluctuations in supply and demand

One of the key characteristics of the Texas electricity system is the sudden fluctuations in supply and demand. With around 26% of their generating capacity coming from the variable renewable energy sources of wind and solar, the total available supply in the system at any given time in the future is never given. Unexpected weather conditions can arise, and suddenly the available supply is drastically reduced from what was expected. In addition, most of the wind and solar capacity is located in remote areas in the western part of the state where sufficient transmission not yet have been developed. Too much variable renewable energy in a small market means that the market will be flooded with extremely low-cost power when the weather conditions allow for full production, while being under-supplied during other weather conditions. This naturally creates volatility in the local prices. As will be explained later in this thesis, certain geographically flexible demand responses, like Bitcoin miners, can mitigate this price volatility by locating themselves in close proximity to the variable renewable energy sources and producing at full capacity during periods of over-supply and low prices, while lowering their production volume during periods of under-supply and high prices.

The big fluctuations in the market are not only coming from the supply side, but from the demand side too. The Texas weather is characterized by sudden, short and unpredictable bursts of extreme heat during the summer, and it is estimated that about half of the state's peak electricity use comes from air conditioning alone (Minton, 2020).

As witnessed in February 2021, not only heat waves are influencing the supply and demand of electricity in Texas. During around 10 days of that month, severe winter storms swept across the state, driving temperatures all the way down to -15°C as in Dallas (Maxouris, 2021), a huge difference from the city's average February temperature of around 11°C (Current Results, 2021). These extreme weather conditions naturally drove up the electricity demand. Normally, the capacity in Texas should have been able to handle such levels of demand, but the weather also reduced the supply by freezing up wind turbines, solar panels, natural gas equipment, coal plants and nuclear reactors. The high demand combined with the low supply led to massive system failure and power outages. Over 4.5 million homes and businesses in the state were left without electricity (Sullivan & Malik, 2021). Such catastrophes show that the need for demand response is not only important for price stability and for securing electricity demand for remote renewable energy projects, but also more importantly to secure supply of electricity to households during extreme and unpredictable events.

4.3 Bitcoin mining in Texas

According to Cambridge Centre for Alternative Finance (2020) and their Bitcoin mining map, around 7.2% of the total Bitcoin mining activity worldwide takes place in the United States. In the US, the biggest mining hubs are in the hydro power states of Washington and New York (Bendiksen & Gibbons, 2019, p. 6), but the industry has seen huge growth in Texas during the last few years, due to the state's cheap electricity and regulatory environment, but also because of opportunities for drastically reducing electricity costs by participating in demand response programs or doing price-responsive demand response. Several mega projects are planned in the state, for example the German company Northern Data's planned facility of 1 GW, which will be the world's biggest Bitcoin mine (Businesswire, 2020), or Argo Blockchain's planned 200 MW facility (Bambysheva, 2021). According to Cambridge University for Alternative Finance (2021), the total electricity draw of the entire Bitcoin mining network is 13.45 GW, and we can see that the new giant projects in Texas are making the state one of the most important locations for Bitcoin mining in the world.

During the last year, there was an immense growth in Bitcoin miners providing demand response services to the grid in Texas. There are two main categories of demand response present in the Texas grid: price-responsive demand response and ancillary service demand response programs (EnelX, 2020). In the following sections, we will take a closer look at them.

4.3.1 Price-responsive bitcoin mining

Price-responsive Bitcoin mining is about locating Bitcoin miners behind-the-meter (BTM) directly at renewable power plants and mining when the market price for electricity is low and refraining from mining when it is high. This is mostly done in West-Texas, where abundant wind resources are creating high volatility in the local electricity prices. As shown in figure 11, the renewable power plant sells electricity to the Bitcoin miner when the market price for electricity is lower than the bitcoin miner's break-even power price, and sells electricity to the market when the market price is higher than the bitcoin miner's break-even power price. This means that the bitcoin miner will always pay marginally more for the renewable power plant's electricity than the market, up to its break-even power price, where it will refrain from buying and instead let the market buy the electricity.

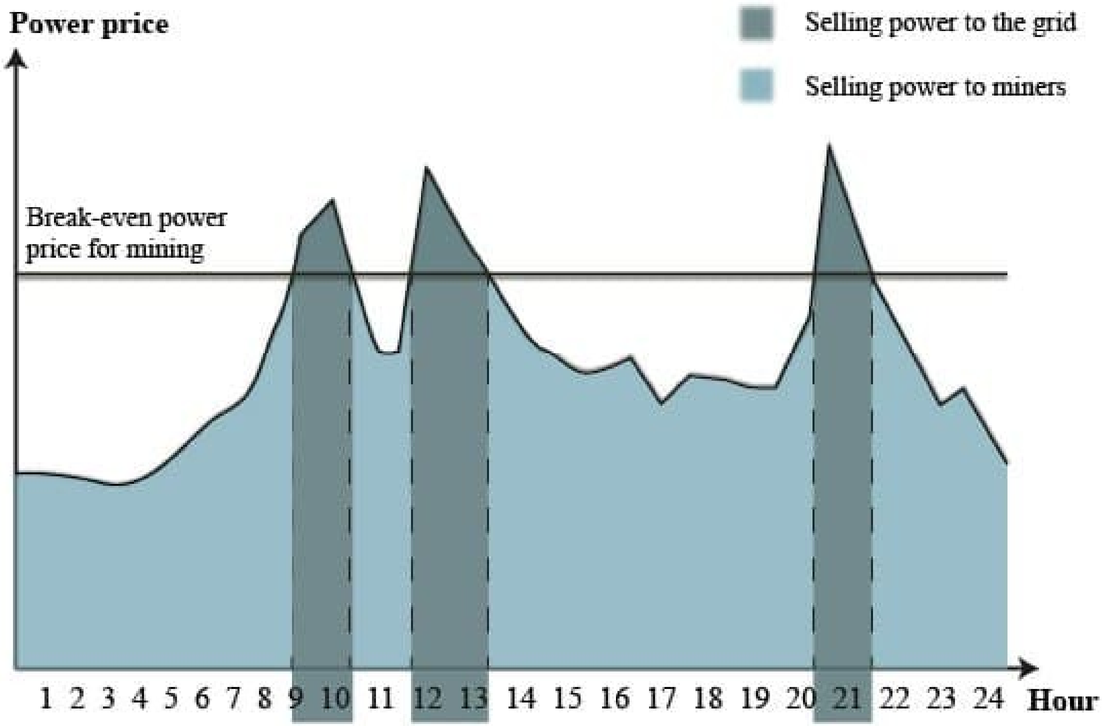
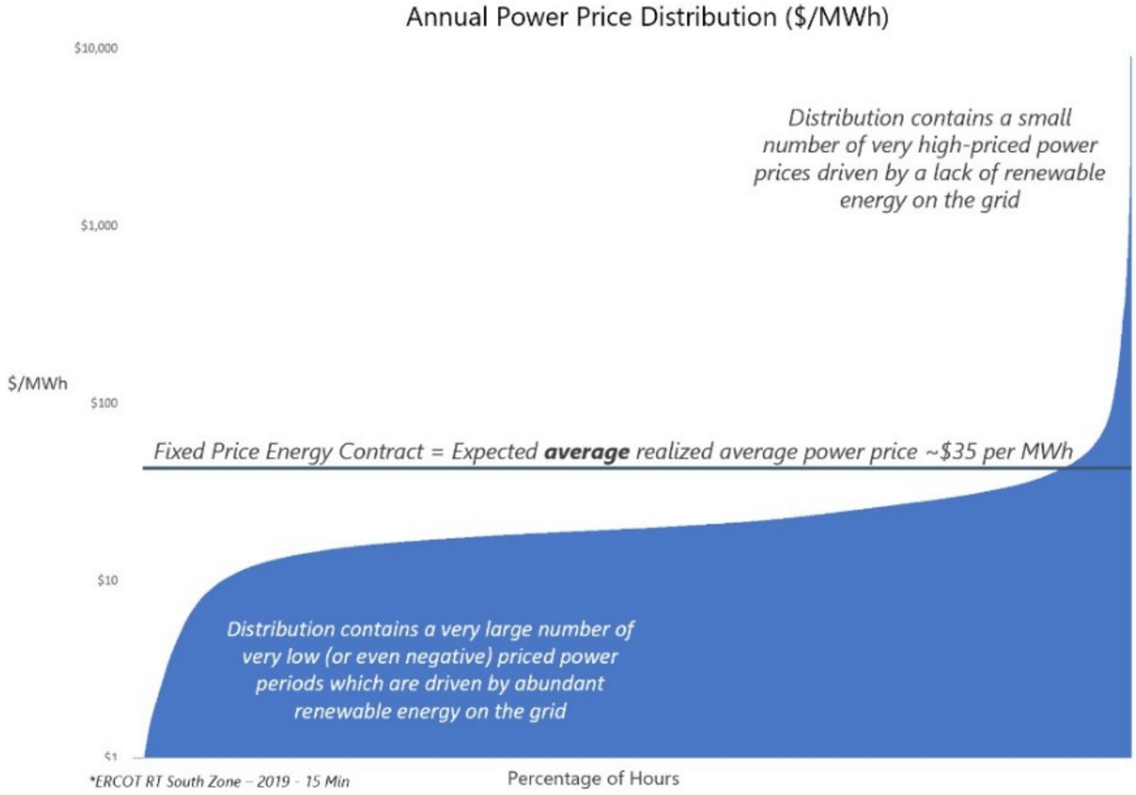


Figure 8: Price-responsive bitcoin mining.

There are two reasons why an operation like this can drastically reduce a bitcoin miner's electricity costs. As McNamara et al. (2019) explains, transmission & Distribution (T&D) costs represents a large portion of the overall price consumers pay for electricity. By buying electricity BTM, a Bitcoin miner can avoid T&D costs. In addition, since the bitcoin miner is able to turn its machines off in response to price spikes, it can cut away the most expensive electricity prices from its bill. As shown in figure 12, in a market like West-Texas' characterized by low prices most of the time but a few extreme price spikes because of a high degree of variable renewable energy and extreme weather events, a Power Purchase Agreement (PPA) will be priced above the median cost of electricity. By not entering a fixed-price PPA, the Bitcoin miner can simply refrain from buying electricity during these spikes and thereby significantly reduce its total electricity costs.

According to industry insiders, by excluding the highest priced hours, a Bitcoin miner in Texas can achieve an average electricity price of around $10-22 per MWh. This price is achieved by curtailing around 15% of the capacity, so that the miner will have an up-time of about 85% (Judge, 2020). Texas can be extremely hot in the summer, and cooling of the hardware has historically been a big challenge for Texas' bitcoin miners. In order to run the miners at full capacity with as high up-time as possible, a Texas' miner will in most cases need expensive liquid cooling systems. One of the advantages with the price-responsive Bitcoin mining strategy is that liquid cooling is not necessarily needed since the miners only operate around 85% of the time. The times when the miners will curtail their energy consumption are also often coinciding with the hottest periods of the summer, since in these periods the electricity will be very expensive due to the high demand for air-conditioning.



Annual Power Price Distribution ($/MWh)

Distribution contains a small number of very high-priced power prices driven by a lack of renewable energy on the grid

Fixed Price Energy Contract = Expected **average** realized average power price ~$35 per MWh

Distribution contains a very large number of very low (or even negative) priced power periods which are driven by abundant renewable energy on the grid

*ERCOT RT South Zone – 2019 - 15 Min

Figure 9: Annual power price distribution (Lancium, 2020).

Price-responsive Bitcoin mining gives Bitcoin miners access to cheap electricity as well as securing a local source of demand for renewable energy projects. This local source of demand will pay marginally higher prices for the electricity than the market up to a certain threshold when the electricity is instead sold to the market. This will be elaborated more into detail in chapter 5.

4.3.2 Bitcoin miners in demand response programs

During the last year, we have seen a high growth in bitcoin miners classified by ERCOT as load resources (LR), a classification enabling them to participate in various day-ahead markets for ancillary services where they sell their capacity to ERCOT. By buying a Bitcoin miner’s capacity, ERCOT has an option to utilize this capacity to stabilize the frequency of the grid given certain frequency deviations. The LR designation can be further broken down into two sub-designations: Controllable Load Resource (CLR) and Non-Controllable Load Resource (NCLR). The main difference between the two is that, as the name suggests, CLRs can control its power consumption with granularity while NCLRs only have two choices: produce at full capacity or turn off the whole load. To earn the CLR designation, a load has to go through rigorous testing procedures as well as having access to specialized software that enables it to respond extremely fast and with high granularity to grid frequency deviations. To be designated as a NCLR is easier, as you only have to show ERCOT that you can respond quickly to frequency deviations without the granularity requirement. Here, an Under-Frequency Relay (UFR) is placed on the mining facility that measures the grid’s frequency and will trip the whole load offline given a certain frequency deviation. While it is easier to be designated as a NCLR, it pays less than the CLR designation since a CLR is allowed to participate in all four of the day-ahead ancillary service capacity markets, while the NCLR only is allowed to participate in one of these markets: Responsive Reserve Service (RRS), which also is the biggest of the them, with an average capacity of around 1500 MW per hour (ERCOT, 2021; Monthly Demand Response from Load Resources). This means that a CLR always can choose between several day-ahead markets and sell its capacity in the highest paying of them, while the NCLR does not have this opportunity. Also, in order to maximize system security, ERCOT has a minimum requirement for how large share of the RRS needs to be provided by CLRs. Since there are much more load resources of the NCLR designation than of the CLR designation, CLRs will most often get a higher price for their capacity in this market than NCLRs.

The day-ahead ancillary services capacity markets provide flexibility to ERCOT, and since a CLR is more flexible than a NCLR it also is more valuable to ERCOT and will therefore get paid more. Nevertheless, participating in demand response can be very lucrative for both CLRs and NCLRs. As seen in figure 13, during the last ten years, the average annual payment for selling capacity in the biggest of these markets, RRS, has consistently been over $100,000 per MW-year. As mentioned, both NCLRs and CLRs can participate in the RRS market, but CLRs can also participate in other markets that often have even higher prices. This means that the average annual payments per MW-year for a CLR will be well over $100,000. Of course there is volatility with respect to the clearing prices in the ancillary services markets, but from sources in the industry, I have been told that a CLR can expect an average payment of around $17 - $20 per MWh, while a NCLR can expect around $8 per MWh. Bitcoin miners like to think about these

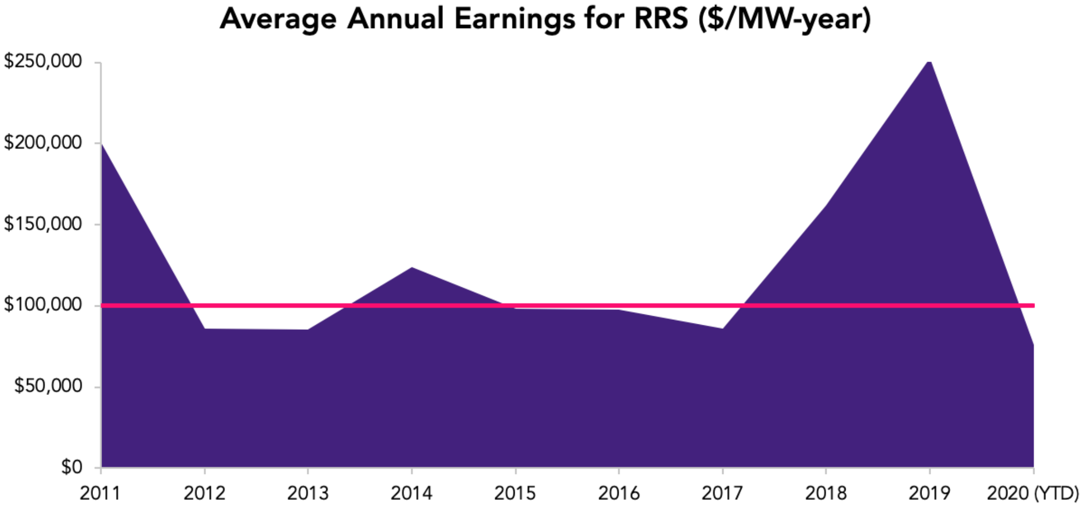
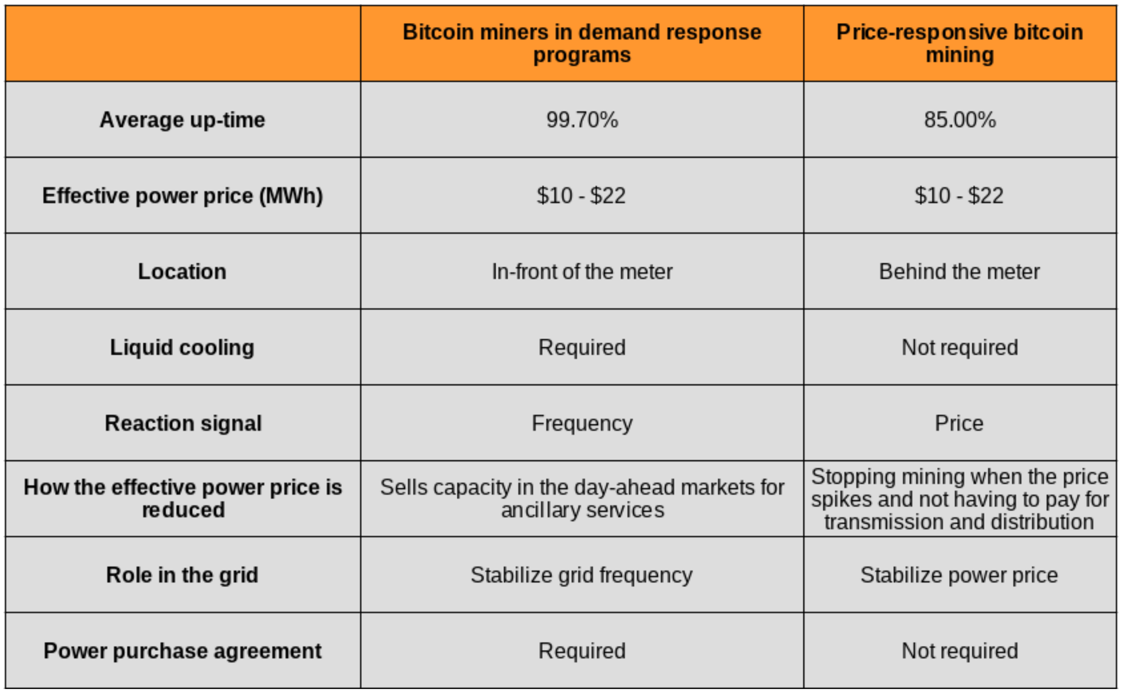


Figure 10: Average annual earnings for RRS (EnelX, 2020).

payments in terms of how they reduce their total electricity price, so if a bitcoin miner has a Power Purchase Agreement (PPA) for $30 per MWh and participate in ancillary service markets as a CLR, its average electricity price after ancillary service payments will be $10 -$13 per MWh. Getting a PPA for $30 per MWh is not unusual in Texas.

In order to participate in these ancillary service markets, a Bitcoin miner must have a power purchase agreement. The miner must lock in a certain capacity for a certain price, so that it can sell an option on this capacity in the day-ahead ancillary service markets. The miner will receive a payment for this capacity no matter if ERCOT deploys it or not. According to a Texas Bitcoin miner participating in these markets, the average curtailability for load resources in Texas the last six years is 0.3 percent. This is because load resources function as insurance underwriters for the grid, and ERCOT only deploys these resources during grid emergencies. The load resources provide flexibility to ERCOT, and since a CLR is more flexible than a NCLR it also is more valuable to ERCOT and will therefore get paid more.



	Bitcoin miners in demand response programs	**Price-responsive bitcoin mining**
Average up-time	99.70%	85.00%
Effective power price (MWh)	$10 - $22	$10 - $22
Location	In-front of the meter	Behind the meter
Liquid cooling	Required	Not required
Reaction signal	Frequency	Price
How the effective power price is reduced	Sells capacity in the day-ahead markets for ancillary services	Stopping mining when the price spikes and not having to pay for transmission and distribution
Role in the grid	Stabilize grid frequency	Stabilize power price
Power purchase agreement	Required	Not required

Table 2: Bitcoin miners in demand response programs and price-responsive bitcoin miners.

5 Empirical findings

This chapter will contain an introduction of the findings from collected data and conversations with industry insiders regarding Bitcoin mining as a demand response in the ERCOT-system in Texas. The findings will be organized in the modified PESTEL-analysis which was described in chapter 3, with all the factors grouped into technical, economic, political and environmental factors. Here, the technical factors are the most important, and as described in chapter 2, I have created a framework to evaluate processes' suitability as demand response based on academic and industry literature. If the reader needs an explanation of the different technical factors, I refer to the section about demand response in chapter 2.

5.1 Technical factors

5.1.1 Energy intensity

CBECI (2021) estimates the entire bitcoin mining industry to have a power draw of 16GW, and an annualized consumption of 144TWh. Based on these numbers, and the world total final electricity consumption (IEA, 2020; Electricity Information), bitcoin mining is responsible for around 0.6% of the total electricity consumption globally. This undoubtedly makes Bitcoin mining a highly energy intensive industry. It is also important to find out how the total energy consumption is spread out across all the different miners, based on the competitive dynamics of the industry. If the industry consists of many small scale operations each drawing just a few KWs, the mining processes will be less suitable for usage as demand response than if the industry consists of fewer, but large-scale operations drawing several MWs, since bigger individual loads are easier to manage for demand response than many small ones.

Bitcoin mining is an extremely competitive industry, and since bitcoin is a fungible good, miners compete on costs alone. For a bitcoin miner, one of the simplest ways to push down its costs is through economies of scale, since among other things, scale allows a bitcoin miner to access lower priced electricity and negotiate lower purchase prices for mining machines (ASICs). Bitcoin mining is a relatively simple business with few inputs and outputs. A miner buys specially designed computing hardware called Application-Specific Integrated Circuits (ASICs) and powers them with electricity to earn bitcoins. Blandin et al. (2020), estimated that capital expenditures represent on average 45% of a miner's total costs. The remaining 55% covers operational expenditures, from which 75% is utilized towards electricity payments (Blandin et al., 2020). Based on these estimates, it can be calculated that for the average miner, the electricity costs are about 40% of the total costs. The combination of the importance of having economies of scale and the fact that electricity costs is such a big cost component, makes the individual Bitcoin mining operations into huge electricity consumers.

As explained in section 2.1.3, any process that has an interruptible load of minimum 100 kilowatts is usually a good candidate for demand response. One of the most popular ASICs, Antminer S9, has a power consumption of around 1,4 kilowatts (ASIC Miner Value, 2021), which means that a Bitcoin miner only needs to have around 70 of these in order to draw enough energy to be eligible to participate in demand response. Most mining farms are much bigger than this, and operations drawing over 100 megawatts are not unusual.

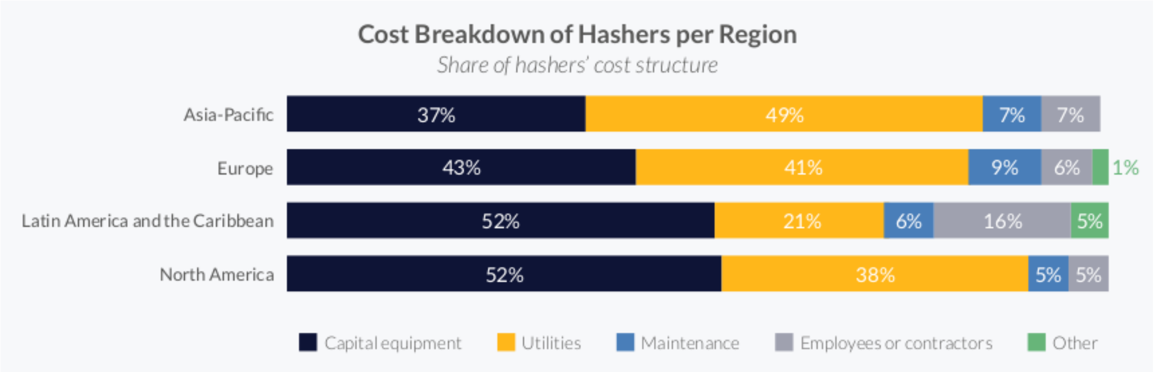


Figure 11: The cost components of bitcoin miners (Blandin et al., 2020).

5.1.2 Reaction time

As explained in section 2.1.3, a process acting as demand response must be able to react quickly as the frequency or price imbalances it is engaged to stabilize most often are short lived. As Shan & Sun (2019) explains, ASICs are computers, and can therefore quickly adjust their energy consumption. The ASICs can be connected to a control panel that lets the administrator adjust their energy consumption at a moment’s notice. In Bitcoin mining as a demand response, this process can be automated based on factors such as electricity price or grid frequency. According to Lancium (2020), their patented demand response software allows Bitcoin miners’ and other data centers to ramp up or down their electricity consumption in as little as five seconds. This reaction time is on par with the fastest reacting peaking plants, and lets Bitcoin miners in Texas sell their capacity in the ancillary services day-ahead markets requiring the fastest reaction times.

5.1.3 Availability

As explained in section 2.1.3, it is important for a process to be available when it is needed for demand response, especially if the process is participating in a formal demand response program.

When it comes to Bitcoin miners’ availability, they are economically incentivized to constantly produce at their full capacity, since they have made significant investments in ASICs that they must earn back. Because of this, Bitcoin miners are highly reliable and stable loads with great availability.

5.1.4 Cost of reacting

Bitcoin mining is a very simple operation: A bitcoin miner owns computing hardware, feeds it with electricity and gets bitcoins in return. It is a probabilistic game where, in the long-term, the amount of bitcoins a miner will get paid depends solely on their computing power, which again depends on their electricity consumption. You can say that the miner transforms electricity into bitcoins. Therefore, whether a bitcoin mine runs in the middle of the day or in the middle of the night does not matter, so bitcoin mining's computations can be characterized as a non-time sensitive computation (Maze-Rothstein, 2021). In addition, there are no clients and no requirements for up-time (Arvanaghi, 2020).

In addition to having no clients and no requirements of up-time, a bitcoin miner has no costs related to the actual down-ramping of its facility's power consumption. ASICs can be turned on and off by the click of a button, and the process can also be entirely automated. This means that the only cost of reacting for a bitcoin miner is the alternative cost of not mining bitcoin during the time the miner is shut down. For all industrial processes utilized as demand response, the alternative cost of not producing will be the minimum cost of reacting, so this makes bitcoin mining's cost of reacting minimal.

5.1.5 Consumption level granularity

As Liegl (2020) explains, physical power plants can usually only increase or decrease output in big increments of 1 megawatt or more, while virtual power plants (VPPs) can increase or decrease output in hyper-granular increments on the kilowatt-level. A VPP consists of several flexible consumers who aggregate their combined demand response capabilities. In this respect, a bitcoin miner can be compared to a VPP, but there is one big difference. A Bitcoin miner already has the capabilities of granularily increasing or decreasing its electricity consumption while the VPP must integrate several flexible customers to get these capabilities. Arvanaghi (2020) describes that miners can, by being shut down in batches, provide the precise wattage the grid needs for demand response. There are several ways a bitcoin miner can granularily adjust their electricity consumption: Miners usually have several hundreds or thousands of ASICs, so they can adjust the total number of ASICs running at any time; they can adjust the effect of each individual ASIC; and they can also potentially adjust the effect of other power drawing equipment, like cooling, although this is not very usual.

As described in chapter 4.3.2, demand response can be done both by processes that can granularily adjust their energy consumption, and by processes that cannot. The difference is that processes that can are able to help the grid in a larger variety of situations. This means more security for the grid manager, and they will therefore usually pay more for demand response services offered by processes that are able to granularily adjust their consumption than for processes that cannot. In chapter 4.3.2, I also explained the differences between the classifications ERCOT gives to their load resources based on their ability to granularily adjust their electricity consumption. A bitcoin miner actually became the first successful load-only Controllable Load Resource (CLR) designation by ERCOT in 2020 (Lancium, 2020; Demand Response). This designation has existed in ERCOT since 2004, but until 2020, only generators had proven to have the granularity capabilities needed for this designation. The fact that a bitcoin miner became the first load resource in ERCOT without generation to get this designation shows how granular their consumption level is.

5.1.6 Geographic flexibility

As explained in section 2.1.3, all processes have constraints limiting their geographic flexibility, although to different degrees. Examples of such constraints include: Access to labor; access to raw materials and other input factors; and access to distribution networks for their products and services.

Bitcoin mining is not a labor intensive industry. When the data center is up and running, the work force mostly consists of technicians who control and configure the machines and other technical equipment. Workers fulfilling the requirements for such roles can be found in most locations, especially considering that a Bitcoin mining facility does not need a large number of workers.

When it comes to access to raw materials and other input factors, bitcoin miners need ASICs, electricity and cooling systems. ASICs and cooling systems are capital expenditures and only need to be deployed once, and can practically be shipped to any location with road connection. As described by Bendiksen & Gibbons (2019), up until just a couple of years ago, it was more important for miners to have quick access to the newest and most powerful ASICs, while having access to the cheapest possible electricity came in second. As most novel technologies, ASICs were improving at such a rapid rate that miners constantly had to upgrade them in order to stay competitive. Since the biggest ASIC manufacturers are located in China, it was natural for miners to locate themselves there too so that they could get their hands on the newest machines before their western competitors. Therefore, in the first years of ASICs mining, miners were significantly less geographically flexible than they are now, since they had such big advantages of locating themselves in China, close to their suppliers of ASICs. This has now changed, and most miners today prioritize having access to cheap electricity over having quick access to the newest ASICs. The reason is that the technological improvement rate of ASICs has drastically slowed down, leading to a longer life-time and thus less importance of having

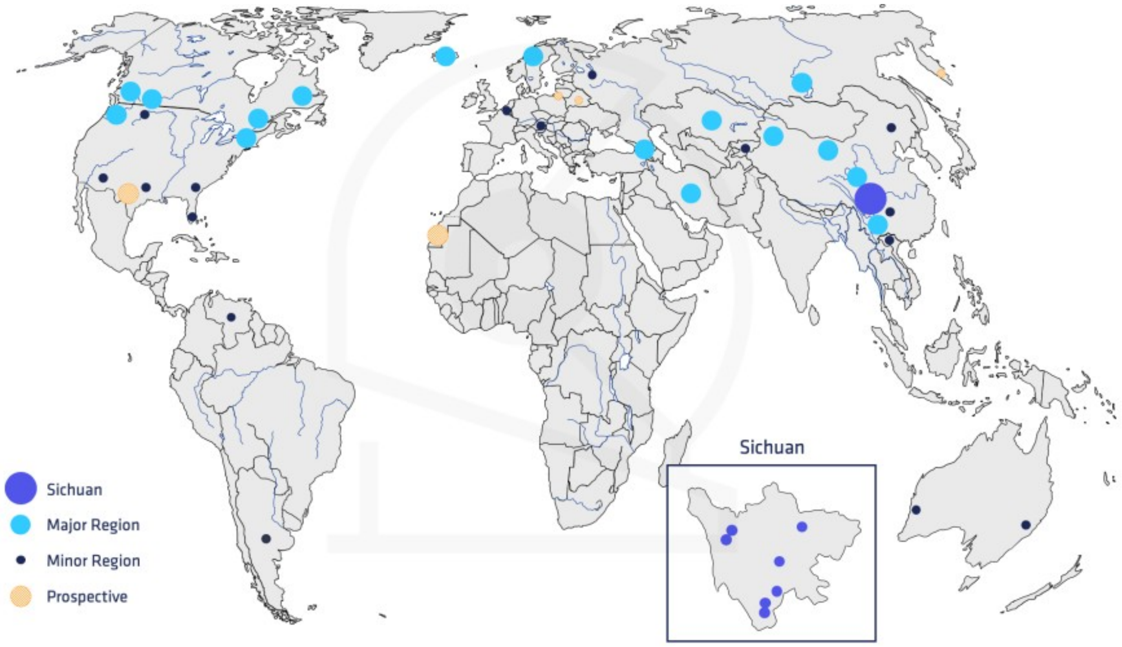


Figure 12: Bitcoin mining map (Bendiksen & Gibbons, 2019)

the newest gear. Therefore, today’s Bitcoin miners are not tied to any specific geographic location for access to equipment.

The biggest input factor for a Bitcoin miner is electricity, and miners are dependent on having access to cheaper electricity than their competitors in order to stay profitable over time. This means that Bitcoin miners are geographically tied to places where the electricity is cheap. Nevertheless, as explained in chapter 4.3, Bitcoin miners participating in demand response in Texas can potentially reduce their electricity costs by well over 50%. These cost savings from demand response can open up many new locations for Bitcoin miners where previously the electricity was too expensive, of course given that they have possibilities for doing demand response there. Since the payouts and cost savings for providing demand response services can be so big, they will most likely give Bitcoin miners sufficiently low electricity prices so that it is economically viable for them to locate themselves in almost any place where demand response is needed.

When it comes to access to distribution networks for their products, Fridgen et al. (2017; p. 400) explain that bitcoin is an information good which is easily transferable through communication networks, so therefore, power-intensive processing of information goods is not tied to any specific location. In other words, bitcoin miners distribute their product, processing power, over the internet. Their payments in bitcoin are also distributed to them through the internet. Therefore, when it comes to the distribution of products and services, bitcoin is extremely geographically flexible.

5.2 Economic factors

5.2.1 Volatility

The demand response resources should ideally be available to the grid for many years, in order to give the grid long-term stability. The grid managers must be able to plan ahead, and this can be difficult if demand response resources suddenly disappear from the system, since it is difficult to replace their flexibility in a short time. If a grid loses demand response resources, it needs to replace them either with flexibility from the supply side or new flexibility on the demand side. Flexibility on the supply side mostly comes from peaking plants, which can take several years to build. On the other hand, flexibility on the demand side is from new demand response resources, but their capacity can be limited, and if big consumers were not already able to sell their capacity in the ancillary services markets before the loss of the old demand response capacity, it is unlikely that they will be able to after. Of course, in a scenario where a lot of the demand response capacity suddenly disappeared, the price for demand response capacity in the ancillary services day-ahead markets would drastically increase, but the grid could still have problems in integrating enough new resources to make up for the lost ones. Especially in a low capacity margin market like the ERCOT-system, this could be detrimental for the system stability, and could potentially lead to blackouts. It is therefore important that the bitcoin miners have a long time-horizon when establishing themselves as demand response resources. Here, a long time-horizon means that the bitcoin miners will not just suddenly shut down their operations, leading to a sudden loss of demand response capacity for the grid.

The only reason why a bitcoin miner will shut down its operations voluntarily, is if mining becomes unprofitable for them. Bendiksen & Gibbons (2019) describe the competitive dynamics of the Bitcoin mining industry and for which bitcoin prices a bitcoin miner will shut down its operations. They here provide two metrics: ROI break-even level and cash-flow break-even level. The ROI break-even level is the price level of bitcoin where mining is unprofitable when all costs are included, while the cash-flow break-even level is the price level of bitcoin where the payments from mining not cover the miner’s marginal costs. The capital investments a bitcoin miner makes in order to start mining is a sunk-cost, and the miner must utilize this capital as much as possible to earn back its investments. This means that the miner only will stop mining if the bitcoin price falls below its cash-flow break-even level. If the bitcoin price is lower than a miner’s ROI break-even level, the miner’s capital will slowly be eaten up, but the miner will not necessarily turn off its machines. The cash-flow break-even level is usually significantly lower than the ROI break-even level, meaning that a large decline in the bitcoin price not immediately pushes out most bitcoin miners from the market. Only the marginal miners are pushed out, i.e. the miners with the highest marginal costs. Since about 85% of the marginal costs is electricity (Bendiksen & Gibbons, 2019; p. 4), a sudden, large reduction in the bitcoin price will push out the miners with the highest electricity prices first, and then gradually miners who pay medium prices. Miners on the lowest side of the cost spectrum might never be affected almost no matter the price decline because of the difficulty adjustment ensuring that the remaining miners on the network will get a larger share of the block rewards when other miners disappear. As explained in chapter 4.3, participating in demand response can significantly reduce a bitcoin miner's electricity prices to the point that it can enjoy some of the lowest prices in the industry. This means that miners doing demand response in most cases will be able to resist the high volatility of mining.

It is still important to dive deeper into the volatility of mining and explore if there are ways a miner can hedge or limit its risks. For miners, there are essentially two sources of volatility influencing their revenues: Price volatility and production volume volatility.

Everyone involved with Bitcoin knows that the price volatility can be high, and how this affects bitcoin miners is described above. A Bitcoin miner has possibilities to hedge price volatility by shorting bitcoin futures. This is still an insufficient hedging strategy in itself since a bitcoin miner never can be certain of how many bitcoins they will mine, especially in the long-term. The variability in how many bitcoins a miner will mine is called production volume volatility. In the short term, as long as a miner is part of a mining pool, it can be fairly certain on the number of bitcoins it will be paid. This is based on the miner's share of the total computing power of all the Bitcoin miners combined. For example, if a miner has 1% of the computing power in the network, it can be fairly certain that it will receive around 1% of the newly minted bitcoins in the short to medium term. The problem is that the miner has no influence or knowledge of how the computing power of the other Bitcoin miners will develop in the future. If for example, the computing power of all the other miners double while our miner not increases its capacity, its share of the total computing power will halve from 1% to 0.5%. This means that it can expect to receive half as many bitcoins now as before. This is of course a risk for the miner, and as all risks, it should be mitigated.

As described above, simply hedging the price volatility by shorting bitcoin futures is insufficient since the miner never knows how many bitcoins it will mine in the future. Therefore, there is a lot of focus in the industry right now on how to hedge the production volume volatility. There exist mainly three instruments for hedging the production volume volatility: Difficulty derivatives, hash-rate derivatives and hash-rate tokens. These tools will not be described in detail in this thesis, but they are all very new concepts and not widely adopted yet. As Tu (2020) explains, miners have historically been relatively reluctant to hedge their risks, as mining so far has been a very profitable business without the need to hedge. This is slowly changing, with the introduction of the aforementioned instruments, as well as the growing institutionalization of players in the mining industry (Tu, 2020).

Similarly to bitcoin miners, most industrial companies are subject to price volatility, but the volatility in the price of Bitcoin is higher than for most other products. When it comes to production volume volatility, this is another source of external risk for bitcoin miners that companies in most other industries do not have to deal with. Therefore, to sum up this section, the total external risks from various forms of volatility is considered much higher than in most other industries, and the means for hedging these risks are also not yet sufficiently developed. Nevertheless, with the growing institutionalization of the industry there is huge enthusiasm for these hedging tools, and it is expected that they soon will be widely adopted in the industry.

5.2.2 Procurement of ASICs

The machines bitcoin miners utilize are called application specific integrated circuits (ASICs), and are specially made to serve only one purpose: solve bitcoin mining’s algorithm as fast and energy-efficient as possible. The market is dominated by a handful of companies, where the two biggest, Bitmain and MicroBT have a combined market share of around 80% (Redman, 2020). This oligopolic market structure naturally give the manufacturers a lot of negotiating power, especially when the market price of bitcoin is increasing, since miners then are desperate for getting their hands on new machines. When writing this thesis, the bitcoin price is in one of its biggest up-trends throughout history, and the ASIC manufacturers are not able to produce enough ASICs for the market, and miners who are lucky enough to get their orders confirmed must pay big deposits up-front and will not receive their new ASICs before several months. In addition, when the price of bitcoin increases, the higher profitability of mining naturally drives the price of ASICs up. This makes procurement of ASICs a barrier of entry to bitcoin mining, especially during a bull market. This barrier to entry increases the profitability of existing mining companies who already own ASICs, since the time-lag between the bitcoin price increase and the new mining capacity coming into the market to compete, ensures several months of super profits for the existing miners. This is important to take into consideration when assessing bitcoin mining as a demand response, since this factor is the single biggest barrier to increasing the power draw of the bitcoin mining network, where some of this power draw could have been used for demand response purposes.

5.2.3 Cooling of ASICs

A big part of the electricity required to run ASICs are transformed into heat, and this heat must be cooled or transported away to prevent overheating of the machines. Miners generally have two choices for cooling systems: Air-based cooling and immersion cooling. Air-based cooling is the traditional way of cooling where cool air is blown through the equipment, while immersion cooling is a new technology where the mining rigs are immersed into a special liquid that runs through them and cools them down.

Air-based cooling systems are cheaper and require less capital expenditures than immersion cooling systems. Because of this, many miners are locating themselves in colder climates like the Nordics, Russia, Washington State and New York State, where the cooling requirements are lower and they can get away with cheaper air-based cooling systems. Miners located in hot regions like Texas generally must use immersion cooling systems if they want to operate during the hottest periods of the year. Up until the last couple of years ago, the climate of Texas was considered too hot for mining, but the development of immersion cooling technology have enabled miners to locate themselves there.

As explained in chapter 4.3, there are two main categories of Bitcoin miners in Texas doing demand response. Firstly, we have miners participating in formal demand response programs, who sell their capacity in various day-ahead markets for ancillary services. The capacity is sold on an hour basis the next day, and if a miner has sold its capacity over an hour the next day, the miner is required by ERCOT to consume at minimum the level of the sold capacity during this hour. For example, if a miner on Monday sells 30 megawatts of capacity in the day-ahead market for between 1PM and 2PM on Tuesday, the miner is required to actually consume at minimum 30 megawatts between 1PM and 2PM on Tuesday. This means that a miner in a demand response program cannot turn off its miners due to overheating during a time it has sold its capacity. In addition, the clearing prices for ancillary services will usually be highest during the hottest days of the year, so if the miner is not able to run its mining facility at full capacity during these times, it will lose income from the ancillary services markets. A miner acting as a load resource can expect an up-time of around 99.7%, and to achieve this up-time in the hot climate of Texas, an immersion cooling system is needed. As mentioned, immersion cooling systems will drastically increase the capital expenditures, but it also has many advantages. It draws less electricity than air-based cooling; it prolongs the lifetime of the ASICs; and it also enables the ASICs to be overclocked, which means that the machines can be run on a higher effect than usually.

The other category of Bitcoin miners in Texas doing demand response is price-responsive Bitcoin miners. As explained further in chapter 4.3, they locate themselves close to renewable energy projects and mine when the price for electricity is low and refrains from mining when the electricity price peaks. These miners are only aiming for an up-time of around 85%, which means that they have significantly less cooling requirements than the load resource miners. This is because they will turn off their miners in response to electricity price spikes, and in Texas the reason behind price spikes is usually increased demand during hot weather because of air-conditioning. This means that the price-responsive miners naturally will turn off their miners on the hottest days, since the electricity price also spikes on these days. Because of this, cooling is of less significance for them and they can use air-based cooling systems, which requires much less capital expenditures.

The cooling requirements are important to consider when assessing Bitcoin mining as a demand response, since in many locations in need of demand response, hot climate can introduce the need for expensive cooling systems. This increases capital expenditures of projects, and ultimately makes it even more important to have access to cheap electricity to make up for it.

5.2.4 Power purchase agreements

In order to being part of a demand response program, a Bitcoin miner will need a power purchase agreement (PPA). A power purchase agreement requires collateral, and the collateral requirements are stricter for new entities. This is a barrier to entry for bitcoin miners, but it also increases the need for long-term planning, since a customer who already have a PPA will need to earn back the collateral. Because of this, the grid manager can be more certain that bitcoin miners participating in demand response programs are planning long-term and will fulfill their requirements.

As explained in chapter 4.3, price-responsive bitcoin miners do not need to arrange PPAs, since the foundation of their power strategy is to be able to choose when to buy electricity, so that they can avoid the highest prices. Because of this, price-responsive miners are not subject to the same collateral requirements as miners participating in formal demand response programs.

5.3 Political factors

5.3.1 Market structure

There are specific market structures and regulations that enable Bitcoin mining as a demand response in the ERCOT system. I have found seven factors that I will explain here: Cheap electricity; isolated grid; functioning ancillary service markets; volatile electricity prices; high share of renewable energy; extreme weather; deregulated market; and Bitcoin-friendliness.

Unfortunately, I have not had the time to look for other electric power systems where Bitcoin mining could be suitable as a demand response, but the reader can use the factors provided here to search for electric power systems with potential. The factors are:

Cheap electricity

As mentioned several times in this thesis, a Bitcoin miner must have access to cheap electricity if it is going to stay competitive. Although participating in demand response in Texas can lower a Bitcoin miner's cost of electricity by over 50%, as I explained in chapter 4.3, I do not believe this huge price advantage will last very many years as the extreme competition in the bitcoin mining sector will force down the average electricity price of miners, thus reducing the competitive advantage of doing demand response. A miner might establish itself in a market with expensive electricity prices where they have demand response programs that can drive down the miner's cost of electricity so that it is economical, but my point is that in the long-term, this miner will likely get out-competed by miners who have a low cost of electricity before any demand response initiatives are factored in. An example of a location with functioning demand response programs but expensive electricity is Australia (Carabott, 2021).

Isolated grid

There are three main grids in the United States: The Eastern Interconnection, the Western Interconnection and the Texas Interconnection. The Texas Interconnection is not connected to the other grids and is therefore effectively an island in this respect. Import and export is one of the most effective ways of balancing the electricity market, but Texas does not have this opportunity. This lack of import and export capacity means that they have to rely more on other stabilization measures to balance their system. Demand response is one such measure. The importance of demand response in Texas due to the grid’s isolation increases the needed capacity of demand response, which creates more room for flexible loads like Bitcoin miners to offer this capacity. In addition, the higher demand for ancillary services sold by Bitcoin miners increases the clearing prices and thus the profitability of Bitcoin miners selling this capacity. For many years, the prices for ancillary services in Texas have been among the highest in the United States.

Functioning ancillary service markets

As explained in chapter 4.3.1, ancillary service markets are day-ahead markets where various flexibility providers can sell their capacity to the grid manager. More specific, the grid manager buys options on demand response resources’ capacity so that it, given certain terms, can instruct them to curtail their load if it is needed for grid stability purposes. Far from all electricity markets have functioning ancillary service markets where loads are allowed to participate. This is vital, as load resource Bitcoin miners are selling their capacity in these markets. Without them, the only possibility left for Bitcoin miners looking to provide demand response services to the grid is price-responsive demand response.

Volatile electricity prices

Volatile electricity prices is especially important for price-responsive Bitcoin miners, as price fluctuations are exactly what they are trying to arbitrage and profit from. The volatility in the electricity prices should also ideally be skewed so that prices are normally very low, but with a small number of times with extremely high prices. As I explained in chapter 4.3.2, a Bitcoin miner in a market like this can lower its electricity costs drastically by not entering a power purchase agreement, but instead turning off its ASICs in response to price spikes.

High share of variable renewable energy

Variable renewable energy like wind and solar is dependent on the weather and is therefore inflexible supply. This means that the larger the share of wind and solar in an energy system, the less flexible is the supply, and a larger share of the flexibility requirements of the system must be provided by resources on the demand-side. Demand response is one of the tools to provide demand-side flexibility to the system, and therefore, the need for demand response will be higher in energy systems where a high share of the capacity is from wind and solar.

Extreme weather

As we have seen in Texas, extreme weather can affect both the demand and the supply of an electric power system. This is more closely explained in chapter 4.2.3. Unpredictable extreme weather can create sudden bursts in the electricity demand, or damage equipment which results in reduced supply. In other words, extreme weather creates instability in electric power systems, both when it comes to the grid frequency but also when it comes to the electricity prices. This creates opportunities for Bitcoin miners to help stabilize the system with their extremely flexible load during extreme weather events.

Deregulated market

The Texas market structure is described in chapter 4.1. The market is deregulated, which has resulted in several beneficial factors for their Bitcoin miners doing demand response. Firstly, Bitcoin miners are able to negotiate directly with power plants without going through an intermediary utility. This means that there are less regulatory barriers for Bitcoin miners doing price-responsive demand response behind-the-meter at wind and solar plants.

Secondly, in a deregulated market, there will be several electric providers competing for customers, instead of just one utility. Many of these electric providers have developed demand response programs that their customers have the ability to participate in. As explained in chapter 4, ERCOT is the operator of the system, and they administer several ancillary service markets where certain consumers can sell their demand response capacity. Electric providers have built programs on top of this market, so that consumers do not have to participate directly, but can do it through them. This makes it much easier for a Bitcoin miner to do demand response, since there are many electric providers who can help them with it.

Bitcoin-friendly

The Bitcoin mining industry remains controversial. In some jurisdictions more so than in others. For a Bitcoin miner to be able to plan long-term, it needs to reduce its regulatory uncertainty, and the best way to do this is to locate itself in a location where the authorities are not hostile towards Bitcoin. One Bitcoin miner I talked to is currently in the process of moving his mining operation from New York to Texas, and his main reason for doing this, in addition to the cheaper electricity in Texas of course, is to reduce the regulatory and politically uncertainty of his operations, since he viewed Texas as a more Bitcoin-friendly state than New York.

5.3.2 Opposition from certain governments

Bitcoin is decentralized and therefore undermines the government's ability to control money. Controlling money is the source of immense power, and some will even claim that it is the foundation of the government. It is therefore not surprising that many governments are against Bitcoin, and a few of them have even outright banned it. Examples of countries with bans or restrictions on the use of Bitcoin include China, Russia, India, Turkey, Iran and Nigeria.

While these countries take such drastic measures in order to protect the government's control over money, other countries are moving in the opposite direction and welcoming Bitcoin. Some of the most Bitcoin-welcoming countries include Japan, South Korea, the Netherlands, Portugal, Switzerland, Georgia, Malta and Singapore, as well as the states Wyoming, Florida and Texas in the United States.

5.3.3 Opposition regarding bitcoin mining's energy consumption

This source of Bitcoin's criticism is specifically targeting mining, and comes from people who complain about Bitcoin mining's energy consumption. I will not dive into their arguments in this thesis, but I nevertheless want to mention that all of their arguments rests on one of two different assumptions:

Assumption 1: The first assumption is that the Bitcoin payment network does not have any value for society and that spending energy on supporting this payment network is essentially wasting energy. Bitcoin supporters on the other hand, have the opinion that the mining process is not wasting energy since their assumption is that a decentralized and trust-less payment system with no need for intermediaries is a valuable good for humanity and thus worth spending energy on.

Assumption 2: The second assumption is that a decentralized payment system like Bitcoin may very well have value for society, but can and should be improved and made more energy-efficient. Elon Musk belongs to this group and has stated that he wants to work on Dogecoin to make it more energy-efficient than Bitcoin (Musk, 2021). Also, some people claim that Ethereum by changing their consensus algorithm from proof-of-work to proof-of-stake will be a more energy-efficient version of Bitcoin. These notions that you can create a more energy-efficient version of Bitcoin without compromising on decentralization and security is heavily disputed in the industry.

What also is interesting is that critics of Bitcoin mining's energy consumption seem to ignore that the estimated penetration rate of renewables is much higher in the mining industry than the world average. Bendiksen & Gibbons (2019) has by breaking down Bitcoin mining by region estimated the renewables penetration to be 73%, against the world average of 28% (IEA, 2020).

So far it looks like these opponents have had limited success in their attempts to attack the Bitcoin mining industry, although they have claimed a few scalps. For example, in 2018 the Norwegian government without warning removed the power-intensive industry's electricity tax discount specifically from bitcoin miners (Bambrough, 2018). This suddenly made bitcoin mining almost infeasible in Norway, and some miners even had to declare bankruptcy. I have also been told from people in the industry that other locations where bitcoin miners already have established themselves suddenly have become less positively inclined towards them. An example of this is upstate New York, where miners have met resistance from local populations because of their huge electricity draw and influence on the local power markets (Solman, 2018).

As Bitcoin grows and its price increases, the energy consumption will also increase, which further will provoke climate activists. It is important to note that in the long-term, Bitcoin's energy consumption will only continue to climb if the bitcoin price more than doubles every four years. The reason for this is that the miners' payments, the block reward, is halving every four years. This is described more into detail in chapter 2.2.2. The halving mechanism will limit Bitcoin's energy consumption and ensure that it does not continue to increase into eternity. Nevertheless, if Bitcoin is going to continue its climb towards being the world's preferred base layer for money, its energy consumption will increase and it will draw even more attention from climate activists than it does now.

5.3.4 Increasing ties to the energy industry

At the same time as some climate activists criticize bitcoin mining, a new group of supporters of bitcoin mining are on the rise: The energy industry. The reason why the energy industry is increasingly getting into bitcoin mining is because of bitcoin mining's technical properties that have been described in previous sections in this chapter. Because of these technical properties of bitcoin mining, there is big potential for energy companies in utilizing Bitcoin mining as many different energy tools, as shown in chapter 6.3. Therefore, the energy industry's interests in the bitcoin mining industry has been growing rapidly lately, as exemplified by the Norwegian energy billionaire Kjell Inge Røkke's $50 million investment into Seetee, a company planning to mine Bitcoin with stranded renewable energy (Røkke, 2021). I reference to chapter 6.2 for more information about the energy industry's growing involvement in Bitcoin mining.

5.4 Environmental factors

5.4.1 Integration of renewable energy

As explained in chapter 2.1.1, the main driving force behind the increasing need for demand flexibility is the growing share of variable renewable energy in the energy mix world-wide. In some electric power systems, like Texas', the need for demand flexibility is further increased because of lack of transmission capacity. In addition, the Texas Interconnection is not connected to other grids and therefore, electricity can neither be imported nor exported. Specifically, in Texas the increasing share of wind and solar in the energy mix without sufficient transmission capacity or demand flexibility have introduced these two main challenges to their electric power system: periodically negative electricity prices and curtailment of renewable energy. Solving these challenges is essential to ensure that we can continue to increase the share of renewable energy in the energy mix in a sustainable way. Descriptions of the challenges along with discussions in how Bitcoin mining can help to solve them are provided here:

Periodically negative electricity prices

Texas has during the last 15 years seen an explosive growth of wind power, and massive solar farms are also planned to be developed during the next few years. A big part of this new variable renewable capacity is located in the remote areas of West-Texas, where the transmission capacity is not sufficient to bring all this new energy to the big markets in the eastern part of the state. The market in West-Texas is not particularly big, and the big share of variable renewable energy combined with extreme weather leads to high volatility in the local electricity prices. Sometimes, the high price volatility in the wind-rich western part of the state results in negative electricity prices. This is because wind and solar have extremely low marginal costs, and as explained by McNamara et al. (2019), turning on and off a wind farm can be both expensive and a time-consuming process. During periods with strong winds combined with low electricity demand, the massive supply of wind can push the prices down to negative levels, where renewable energy plants actually have to pay the consumers to buy their electricity. These periods of negative prices hurt a renewable energy project’s economics, and can drive away investors.

As described earlier in this chapter, price-responsive Bitcoin miners are helping stabilize the electricity prices in local markets by mining when the electricity price is low and refraining from mining when the price spikes. As of writing, there is not sufficient price history in the western markets in Texas to judge if this Bitcoin mining strategy really is stabilizing prices, but according to basic economic theory it should, since buying creates higher demand, all equal leading to higher prices. This means that price-responsive Bitcoin miners are helping to reduce the price lows of the market. As McNamara et al. (2019) explains, a generation station having a behind-the-meter customer on site, for example a Bitcoin miner, may selectively choose whether to supply power to the behind-the-meter (BTM) load or to the grid, or both. During negative market price periods, the operator of the BTM load will charge less to consume excess electricity supplied from the generation station, thus creating a price-floor (McNamara et al., 2019). This reduces the impact of negative electricity prices on wind and solar projects.

Curtailment of renewable energy

Bird, Cochran & Wang (2014) describe curtailment as: “*A Reduction in the output of a generator from what it could otherwise produce given available resources (e.g. wind or sunlight), typically on an involuntary basis.”* As further reported by McNamara et al. (2019), the most common reason for curtailment of wind and solar resources is transmission congestion or lack of transmission access. Wind and solar projects have huge initial capital expenditures with very low operational expenditures. Such a cost structure makes it extremely important to produce whenever possible, since there is a big initial investment that must be paid back. Wind and solar are dependent on the weather, so they already have limits in their possible up-time. Therefore, curtailing, i.e. deliberately choosing not to produce when the wind blows or the sun shines, can have a big impact on the profitability of wind and solar projects.

Having a “customer of last resorts” behind-the-meter turning excess electricity into energy carriers or energy-intensive products is a growing trend in the energy industry. This phenomenon is called “power-to-x” (H2 International, 2019), and can potentially eliminate curtailment since a renewable energy project always will have a customer directly on site ready to buy if the electricity cannot be sold to the market. A promising power-to-x conversion is power-to-hydrogen, but the technologies required here are far from ready for mass adoption. In addition, hydrogen requires a distribution network in order to transport the produced hydrogen from the remote renewable energy site to the customers, which can make the product very expensive for the end-customer.

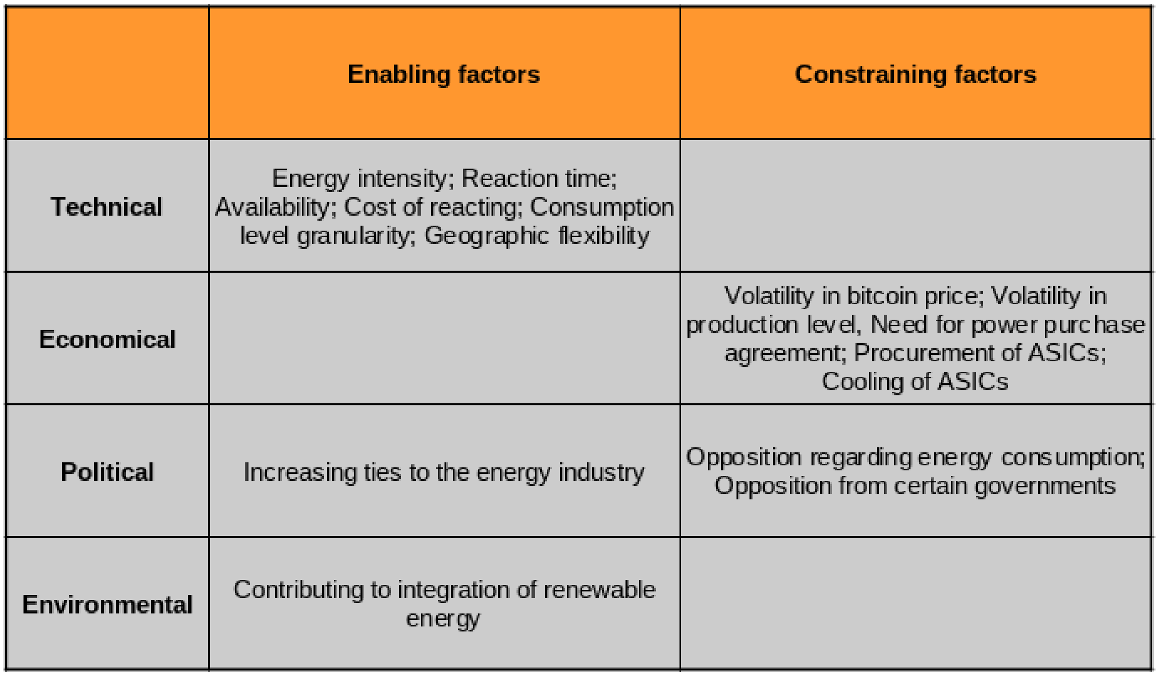
Another power-to-x conversion is power-to-bitcoin. Unlike hydrogen, bitcoin does not require a physical distribution network since the mined bitcoin can be distributed through the internet. Such BTM conversions of electricity to bitcoin are done by price-responsive Bitcoin miners, who are described more into detail in chapter 4.3.2. This is also similar to how Bitcoin mining can help reduce negative electricity prices. A BTM customer of last resort can secure the cash flow of renewable energy projects since they never have to curtail, but can instead direct the excess electricity to the BTM load. Since Bitcoin mining is very suitable as a power-to-x conversion, it is suitable for helping reducing curtailment of renewable energy projects.

6 Discussion and analysis

This chapter will contain a discussion of the case study’s findings and an examination of how the findings will shape the future for utilizing Bitcoin mining as a demand response in electric power systems. Here, the research question will be discussed and answered in the first sub-chapter. The research question will address the enabling and constraining factors for utilizing Bitcoin mining as a demand response. Thereafter follows a sub-chapter with a summary of the other ways in which Bitcoin mining is used as an energy tool. The chapter is then finished with a summary of the analysis, where I share my own thoughts on why I think Bitcoin mining as a demand response is a highly relevant concept in the future of energy.

6.1 Enabling and constraining factors

In chapter 5, important factors for evaluating Bitcoin mining as a demand response are introduced and briefly described. These factors span over the following groups, which



	Enabling factors	**Constraining factors**
Technical	Energy intensity; Reaction time; Availability; Cost of reacting; Consumption level granularity; Geographic flexibility	
Economical		Volatility in bitcoin price; Volatility in production level, Need for power purchase agreement; Procurement of ASICs; Cooling of ASICs
Political	Increasing ties to the energy industry	Opposition regarding energy consumption; Opposition from certain governments
Environmental	Contributing to integration of renewable energy	

Table 3: Enabling and constraining factors for utilizing bitcoin mining as a demand response.

together are summarized in table 3: Technical, economical, political and environmental. This table largely answers the thesis' first case study question: **What are the enabling and constraining factors for utilizing Bitcoin mining as a demand response?** Nevertheless, it is still important to discuss the factors in relation to each other, and how they combined will shape the future of Bitcoin mining as a demand response.

In table 3, the groups of factors are ranked by importance. Also, inside each group, all the factors are ranked after one another. For example, of the technical factors, the most important is energy intensity, followed by reaction time and availability. I will now go through the most important factors and evaluate their relative importance as well as discuss how each factor influences Bitcoin mining as a demand response.

When it comes to the technical factors, we have energy intensity, reaction time, availability, cost of reacting, production level granularity and geographic flexibility. Chapter 2.1.3 contains a description of these factors, while empirical findings of how Bitcoin mining scores on these factors is provided in chapter 5.1. First and foremost, Bitcoin mining is a highly energy intensive process where electricity is the main input factor and the biggest cost component, and its huge total energy consumption makes the industry an important energy consumer globally. As will soon be explained, in addition to being highly energy intensive, other technical characteristics are making the process extremely flexible as well.

Bitcoin miners are almost always available for use as demand response since they, with a few exceptions, always produce at full capacity. Also, since electricity is the biggest cost component for a Bitcoin miner, the miner will be highly incentivized to react to price signals or other factors that can reduce its electricity costs. Having a stable and extremely flexible base-load that also is highly reactive to the electricity price increases the demand-side flexibility and should therefore be attractive for all electric power systems, especially those with lack of supply-side flexibility.

While the high energy intensity and availability are giving Bitcoin mining a very high potential output as a demand response, the other technical characteristics are together ensuring that Bitcoin mining has an extreme flexibility with regards to its electricity consumption. Two of Bitcoin mining’s most outstanding technical factors are an extreme low reaction time and an almost limitless production level granularity. These two factors combined means that a Bitcoin miner can regulate its energy consumption through extremely many levels in just a few seconds. This makes Bitcoin mining highly suitable for frequency stabilizing ancillary services. Because of its production level granularity and short reaction time, Bitcoin miners can compete with the fastest and most granular generators, like they already do in the ancillary services markets in Texas.

Another technical factor that Bitcoin mining scores extremely high on is the cost of reacting. In fact, the only cost of reacting for a Bitcoin miner is the alternative cost of not producing Bitcoin during the time period it has shut off its machinery. This stays in contrast to most other industries where shutting off processes can distort supply chains and bring on losses to customers. For example, critical cloud computing services like Amazon Web Services (AWS) have end-customers relying on maintaining a specific virtual machine instance, while Bitcoin miners do not (Webster, 2020). If AWS suddenly decided to turn off their data centers, their end customers would not be able to use their services and thus incur losses. But if a Bitcoin miner turns off its data centers, nothing happens, since a Bitcoin miner does not have end-consumers.

The last of the technical characteristics enabling Bitcoin mining as a demand response is geographic flexibility. As explained in chapter 5.1.6, the process of Bitcoin mining is not tied to any specific geographic location, other than those with access to cheap electricity. This opens up for Bitcoin mining behind-the-meter directly on wind- or solar farms in remote locations. Many of the best locations for wind and solar are located far away from population centers, for example in deserts. Remote renewable energy plants like these are in most cases able to offer extremely cheap electricity if consumed directly on-site, since the electricity does not have to be transported and the customer can avoid transmission costs. The cheap electricity makes it highly attractive for Bitcoin miners to offer Bitcoin mining as a power-to-x solution directly on-site, where the renewable plant alternates between selling its electricity to the Bitcoin miner or the market. As explained in chapter 5, this process can help secure the cash-flow of remote renewable energy projects by establishing a price floor for its electricity.

Although Bitcoin mining scores extremely high on all the technical factors, there exist some economic constraints. These constraints are: Volatility, procurement of ASICs, cooling of ASICs and power purchase agreements. The Bitcoin price is notoriously volatile and a Bitcoin miner is also exposed to a long-term production volume volatility because of competition. These two factors together, if not hedged, create high volatility and uncertainty in a Bitcoin miners future profits. Because a demand response is providing an important service to the grid, it is important that it is able to plan long-term and not suddenly goes bankrupt so that the grid loses its demand response capacity. Here, it is important to note that Bitcoin miners with very cheap electricity is not at risk of bankruptcy because of volatility, and as explained in chapter 5.2.1, doing demand response strategies can give a Bitcoin miner among the lowest electricity prices in the industry. Nevertheless, since Bitcoin miners are very geographically flexible and always on the lookout for the cheapest possible electricity, I expect more of them to take advantage of power strategies like demand response in the future. More miners doing demand response will lower the average electricity price in the Bitcoin mining network and thus make demand response Bitcoin miners’ cost advantages lower. In addition, since Bitcoin mining is so technically suitable as demand response, Bitcoin miners can potentially “take over” ancillary service markets in specific locations, like in Texas. This will drive down the clearing prices for capacity in the ancillary services markets, and make this demand response strategy less advantageous for Bitcoin miners. Because of this, Bitcoin miners’ cost advantages of participating in this type of demand response are likely to be lower in the future, so the volatility will have more effect on their operations. Still, in the future I expect the necessary instruments for miners who want to hedge their operations to be available, like I explained in chapter 5.2.1. The development of various tools for hedging will be very important for the Bitcoin mining industry in general, and especially for Bitcoin miners doing demand response.

While volatility is an important economic constraint for Bitcoin miners acting as demand response, the other economic constraints: procurement of ASICs; cooling of ASICs; and power purchase agreements; are not. Although they limit the potential growth of the Bitcoin mining network, there exist similar constraints for most other processes used as demand response. For example, a steel producer must also buy expensive equipment and have a power purchase agreement. Such operational growth constraints exists in all industries, not only in the Bitcoin mining industry. They are therefore not deemed very important, but I still included them in this thesis in order to show the reader some of the growth constraints of a Bitcoin miner doing demand response.

The political dimension consists of two main factors: market structure and political reputation of Bitcoin mining. The market structure factor is related to under what conditions Bitcoin mining is best utilized as a demand response, and will be analyzed and discussed in the next sub-chapter.

As explained in chapter 5.3, the opposition from climate activists and certain governments is growing, at the same time as the Bitcoin mining industry's cooperation with the energy sector is increasing. This will ultimately create tensions in the industry, and I expect some jurisdictions to become more hostile towards it. As the Bitcoin network grows, I expect some attacks on the industry, not only from China, but also from certain Western governments trying to minimize their countries' electricity consumption in order to reach international agreements. At the same time as some jurisdictions grow more hostile towards the industry, I think that other's will embrace it, especially energy-rich jurisdictions. As the Bitcoin mining industry gets stronger relationships and shared interests with the energy industry, I expect this industry to be increasingly positive towards Bitcoin mining and to help the sector stand against attacks regarding its electricity consumption. So to sum up, the Bitcoin mining industry will likely remain controversial in the future, but this will be split between Bitcoin friendly countries and Bitcoin non-friendly countries. Also, since Bitcoin mining possess some unique technical characteristics that enable it to be used as several different energy tools, I expect that the energy industry's involvement in the sector will increase drastically, as we for example saw when the Norwegian energy billionaire Kjell Inge Røkke invested $50 million in the Bitcoin venture Seetee (Røkke, 2021). Other examples of such involvements can be found in chapter 6.3. As the reader can see, there are two opposing forces when it comes to the political reputation of Bitcoin mining, and each of them will only grow stronger during the next years, creating big political tensions in the industry.

In the environmental factors, I have listed integration of renewable energy as an enabling factor. As explained in chapter 5.4.1, Bitcoin miners doing the price-responsive demand response strategy can help reduce the cash-flow risk for remote wind and solar projects by locating themselves directly on-site so that the renewable energy project has two options: selling to the market or to the Bitcoin miner. This is especially relevant in geographic areas with periodically negative electricity prices, as will be explained in the next sub-chapter. Many of the areas with the most wind- and solar resources are located in remote locations where transmission is a challenge. Building out long transmission lines to transport electricity from the resource centers to the populations centers can be extremely expensive, as well as politically difficult since the lines must go through vast territories where it is not certain if the local population will support the project. Since it is much easier to build a wind- or solar plant than to build transmission lines, the former is often built before the latter. This introduces congestion problems and the energy effectively gets stranded. If we are to continue the replacement of fossil fuels with renewable energy, we must increasingly tap into solar and wind resources located far away from population centers, such as deserts and oceans. Since transmission of these energy resources is so difficult, it would be very favorable to have consumers directly on-site that can turn the electricity into a value-dense, energy-intensive product that is easier to transport to the population centers than the electricity itself. This concept is called "power-to-x". Price-responsive Bitcoin miners are in fact turning stranded electricity into the product bitcoin and transporting the bitcoins to the market through the internet. Since bitcoin is code, its value-density is near infinite and it is also extremely easy to transport since its done through the internet. Also, as explained in chapter 5.1.1, Bitcoin's energy intensity is very high. This makes bitcoin a fantastic vehicle for transporting stranded renewable energy to the market, which is exactly what price-responsive Bitcoin miners are doing in Texas. This is in line with Fridgen et al. (2021) findings that an integrated energy system consisting of a wind- or solar project with a bitcoin mining data center on-site can increase the net present value of the project by over 30%, in addition to stabilizing the electricity grid.

6.2 Other ways bitcoin mining is used as an energy tool

In addition to being used for demand response purposes, Bitcoin mining is currently being utilized as at least two different tools in energy systems, while being tested as a third one. These tools are: 1) providing a local market for stranded natural gas; 2) securing demand for conventional power plants; and 3) financing remote renewable energy projects with no grid connection. To be clear, these ways of utilizing bitcoin mining as an energy tool does not have anything to do with bitcoin mining as a demand response. I have just included them in my thesis to give the reader more insight into other innovative ways bitcoin mining can potentially help the energy industry.

Providing a local market for stranded natural gas

Bitcoin mining is used to combat gas flaring in oil production in the US and in Russia by providing a local market for the previously stranded natural gas. In the summer of 2020, Equinor, one of the largest energy companies in the world, partnered with the startup Crusoe Energy Solutions to significantly reduce flaring from operations through Bitcoin mining (Arcane Research, 2020). Equinor has since sold the oil field to Grayson Mill Energy (Equinor, 2021). Associated gases is a by-product of oil production, and can either be transported to consumers through a pipeline, turned into liquid gases, flared, or vented into the atmosphere. If it is not economically viable to build pipelines or process the gas into liquids, the oil producer will flare the gas, wasting a potential energy resource and increasing carbon emissions. Instead, as in this case, the oil producer sells the gas to a Bitcoin miner, who has set up a gas-to-electricity generator as well as a mining facility directly on the production site. This introduces a new revenue source for the oil company and reduces carbon emissions at the same time, as long as the alternative is not to shut down production. The solution is not only used by Equinor, but many other oil producers operating in the US (Oilman Magazine, 2020), as well as the oil giant Gazpromneft in Russia (Baydakova, 2020). In 2019, the total volume of gas flared globally was around 150 billion cubic meters (Wheeler, E., 2020), which before factoring in the energy efficiency is equivalent to approximately 1625 TWh. This is around 13 times the estimated annual energy consumption of Bitcoin mining of 122 TWh (CBECI, 2021), and illustrates what enormous potential lies here.

Securing demand for conventional power plants

A conventional power plant can install Bitcoin miners on-site and mine with their own electricity. Here, the Bitcoin miners act as buyers of last resort by securing demand and giving the power plant an alternative way to monetize its electricity. Example of a power plant currently doing this is the New York gas power plant Greenidge Generation that was almost pushed out of the market by cheaper shale natural gas supplies and coal exports from China (Anzalone, 2020), but decided to install Bitcoin mining rigs in order to secure demand for their electricity. The company switches between selling electricity to the market and mining Bitcoin depending on what is most profitable. Similar projects can be found in Ukraine, where two different government owned nuclear power plants are planning to set up data centers and Bitcoin mining facilities on-site (Moss, 2021). Nuclear power plants run best on full capacity, but the electricity demand has been gradually decreasing in Ukraine during the last few years (IEA, 2021, Ukraine). Bitcoin mining is a way for plants like these to export their electricity when local demand fails.

Financing remote renewable energy projects with no grid connection

The fifth example is the company Soluna which is researching how to fully finance remote renewable energy projects with Bitcoin mining. They own a 37,000 acre site in

Morocco where they intend to develop a wind farm (Soluna, 2019). The site is located by the coast in the southern part of Morocco, one of the world's windiest sites. The problem is that it almost does not live people in the area, and it is not economically feasible to build a transmission line all the way to the northern part of the country, where most of the population live. Because of this, these wind resources have been stranded until now. Soluna plan to finance the wind farm with Bitcoin mining and similar data center activities that are located directly on site. This way they can develop the wind farm in gradual steps together with the Bitcoin mining facilities. When the wind farm has reached enough scale, it can be connected to the Moroccan grid system, and sell electricity to this market in addition to selling to the local Bitcoin miners.

6.3 Bitcoin mining demand response in a wider setting

As explained in chapter 2.1.1, the increasing share of wind and solar in the electricity mix world-wide comes with huge challenges related to the intermittency of these energy sources. In traditional electric power systems, the supply-side was responsible for providing the flexibility needed. In modern electric power systems on the other hand, the responsibilities for providing flexibility is pushed over to the demand-side. Since solar and wind are dependent on the weather, consumers will increasingly have to adapt their load profiles to when the weather allows for generation. This problem of intermittency of supply can be solved with batteries, import or export, hydrogen or demand response. Demand response stands out as the cheapest and most available solution today (Heffron et al., 2020). While the infrastructure and technology required for widespread adoption of batteries or hydrogen is not yet available, industrial processes with interruptible loads that can be used for demand response already exist in large numbers (Shore et al., 2016). In addition, I believe that demand response with industrial processes will always be more economically viable than batteries and hydrogen since industrial processes engaged in demand response sell both their flexibility and their produced goods. This is contrary to batteries and hydrogen who only sell one product: flexibility. I am not saying here that demand response is the one and only superior solution to the intermittency problem.

What I am saying is that at this time, it is the most economically viable and available solution. Given some time, when battery and hydrogen technologies become more mature, they might be able to provide cheaper flexibility than demand response resources in certain locations and circumstances. Hydrogen is especially suited for providing seasonal flexibility, but demand response is still the best solution when it comes to short-term flexibility, as shown in figure 3. Providing flexibility to the electric power system of the future is super important and our greatest energy challenge today, and a combination of different types of demand-side flexibility is necessary. To sum up, in order to increase the share of variable renewable energy on the supply-side, we need a higher share of the demand-side to consist of interruptible loads.

Bitcoin mining is the ultimate interruptible load. It is a stable load that can be rapidly adjusted up or down with extreme precision, at no extra costs. With internet connection and access to electricity as the only geographic requirements, Bitcoin miners are also extremely geographically flexible and can easily locate themselves exactly where demand flexibility is needed. The last point is very important, as the need for demand flexibility varies significantly between different locations. This combination of electricity consumption characteristics places the Bitcoin mining industry in a unique position to provide flexibility to the low carbon energy system of the future. There are no other industrial processes that can match Bitcoin mining's potential as an interruptible load. The closest are probably other data center processes, which share many traits with Bitcoin mining, but their biggest downside is that they are dependent on serving specific customers and therefore cannot just shut down their operations. Said differently, they have a high cost of reacting while Bitcoin mining has minimal costs of reacting.

Being the ultimate interruptible load makes Bitcoin mining extremely suitable for demand response. By providing demand flexibility, Bitcoin mining can help integrate wind and solar. For system stability and security of supply reasons, a bigger share of wind and solar in the energy mix forces us to look to the consumers for flexibility. An energy system with a high share of variable renewable energy without the demand flexibility needed is a risky system doomed for failure. Therefore, we are completely dependent on flexible consumers like Bitcoin miners in order to continue the transition towards renewable energy. In addition, since Bitcoin mining is largely a location independent process, it can be located in close proximity to renewable energy projects in smaller markets to secure demand for these projects. As explained in chapter 4, having a Bitcoin mine behind-the-meter on a renewable energy project secures demand for the electricity and can increase the profitability of such projects. Increased profitability of renewable energy projects means that financing them becomes easier, which again leads to more development. More development will again lead to lower prices of renewable energy, referring to Swanson's law (Partain et al., 2016). For these reasons, I believe it is fair to say that Bitcoin mining as a demand response is helping the transition to wind and solar, and that this side of Bitcoin mining's energy consumption deserves more attention.

As of writing, there is a very one-sided debate going on regarding Bitcoin mining's energy consumption. Opponents of Bitcoin are extremely focused on only one metric here: How much energy Bitcoin mining consumes annually. They do not dive deeper into the case, and therefore fail to take into account how this energy is consumed and the positive externalities Bitcoin has on energy markets because of its unique properties as an interruptible load. In reality, Bitcoin mining is one of the global industries with the highest renewable penetration, ranging from about 40% to over 70%, depending on which researcher you ask (Blandin et al., 2020) (Bendiksen & Gibbons, 2019). Many mining facilities are located far away from population centers where there is access to extremely cheap energy. If energy is cheap it is usually because there is very little demand for it. I know that this debate will go on and only grow as Bitcoin grows. It is very important that the participants in this debate have full information about how Bitcoin consumes energy and not just hide behind the simple statistic of its yearly energy consumption. It is necessary to go deeper than that, since Bitcoin mining consumes energy differently than most other industries. In addition, given its properties as an interruptible load, it can contribute to increase the share of renewable energy through providing flexibility.

7 Conclusion

In this master's thesis I aimed to answer the following question:

What are the enabling and constraining factors for utilizing Bitcoin mining as a demand response?

I identified these factors by doing a case study of bitcoin mining as a demand response in the ERCOT-system in Texas. The factors I identified were broken down into the technical, economical, political and environmental groups. I found many enabling factors, but also some constraining factors. The enabling factors mostly come from the technical factor group, and are: High energy intensity, low reaction time, high availability, low cost of reacting, high production level granularity and high geographic flexibility. In addition, in the environmental factor group, I found that Bitcoin mining can help integrate renewable energy by securing the cash flows of remote wind and solar plants through doing price-responsive demand response as I explained in chapter 6.3.

Although bitcoin mining is extremely suitable as a demand response judged purely by the technical factors, as outlined in chapter 5.1, there are a few constraining factors, such as the high volatility of income for Bitcoin miners. It is highly likely that Bitcoin miners will have better possibilities for hedging in the future to counteract this volatility, since currently the industry is very focused on the development of the financial instruments needed. Another constraining factor comes from the political group. Bitcoin mining is meeting opposition from opponents of its energy consumption and governments, and this opposition has been growing in pace with the Bitcoin network's growth and the resulting rise in Bitcoin mining's energy consumption. This can make Bitcoin mining unfeasible in certain jurisdictions where these opponents are able to influence lawmakers or other powerful forces to work against Bitcoin miners. On the other hand, the Bitcoin mining sector's ties to the energy industry are growing. This is a very politically connected industry that has a long history of closely cooperating with governments. With their increasing support, I expect that the Bitcoin mining industry will be able to withstand the growing sceptisism towards this particular form of demand response mechanism. I think the result will be that Bitcoin mining becomes politically unfeasible in certain locations while highly welcomed in other.

The main contributions of this master thesis has been to investigate the feasibility of utilizing Bitcoin mining for demand response. I did this by creating a framework for enabling and constraining factors which are summarized in table 3. These findings support existing literature on bitcoin mining as a demand response. Similarly to Fridgen et al. (2021), I found that bitcoin mining is highly suitable as a demand response judged by its technical power consumption characteristics, and therefore can help both to integrate renewable energy and to stabilize the grid. Demand response increases the demand-side flexibility in the system, which Fernandez & Taibi (2019, p. 7) defines like this:

«A part of the demand, including that coming from the electrification of other energy sectors, that could be reduced, increased or shifted in a specific period of time to: 1) facilitate integration of variable renewable energy (VRE) by reshaping load profiles to match VRE generation, 2) reduce peak load and seasonality and 3) reduce production costs by shifting the load from periods with high price of supply to periods with lower prices.»

From 1) it follows that since bitcoin mining is a flexible load, it increases the demand-side flexibility in the system and therefore facilitates integration of variable renewable energy by reshaping load profiles to match VRE generation. This is highly relevant today since we are desperately trying to integrate renewable energy into the grid, at the same time as bitcoin mining is subject to a lot of criticism for being a big energy consuming industry. Things may not be as dark as the critics try to make it seem like, and the bitcoin mining industry may actually be a net positive for the climate.

For a demand response, an assessment of the technical factors is most important, and I therefore created a technical framework for assessing processes' technical suitability as demand response. This framework was used to assess Bitcoin mining, and can also be used to assess other processes' technical suitability as demand response. For example, it can be used to compare the technical suitability of different industrial processes as demand response, for example Bitcoin mining versus other data center processes like cloud storage. I have chosen to call my framework “Demand Response Flexibility Factors”, and it can be found in chapter 2.1.3. This is the second contribution of my thesis.

The third contribution of this thesis is the conditions that a location should fulfill to make it optimal to use Bitcoin mining as a demand response there. These conditions can be used by Bitcoin miners that are eager to lower their electricity costs by doing demand response to search for promising locations all over the globe. These conditions can be found in chapter 5.3.1

There are some limitations in this research, as described in chapter 3.3. First and foremost, Bitcoin mining as demand response is a very new concept and there exists little publicly available information about it. Because of this, a big part of the collected information came from interviews with industry insiders. Industry insiders naturally have incentives to talk positively about their industries and their operations, so you can never be 100% secure on the reliability of such information. On the other hand, industry insiders are clearly the most knowledgeable people of this topic, and writing this thesis without their information would have been impossible. One thing I wish I was able to was to interview people directly from ERCOT, as I only had the opportunity to speak with Bitcoin miners. ERCOT provides a lot of information about their demand response programs on their website, but it would still be beneficial to interview them and get actual numbers on how the Bitcoin miners provide them with capacity for demand response, and how they feel it helps them.

There exists very little research on bitcoin mining generally and particularly when it comes to the process’ electricity consumption. The sector is subject to a lot of scrutiny and criticism regarding its big energy consumption, but almost all this criticism has root in elements that are very simple to measure and quote, like the total energy consumption of the industry in TWh. Only referencing to bitcoin mining’s total energy consumption without taking into account how this energy is consumed and the purpose it serves is not helpful in the debate. Therefore, more general research about bitcoin mining's energy consumption is needed. Particularly, we need further research on the other ways in which Bitcoin mining can be used as energy tools. It would be beneficial to know the total potentiality of how Bitcoin mining can help the energy sector, aside from stabilizing the grid through demand response. For example mitigating gas flaring by mining Bitcoin with stranded natural gas, or financing remote renewable energy projects not yet connected to the grid. A brief overview of this is provided in chapter 6.3.

Further research can also be made regarding in what geographic area bitcoin mining is best suitable as a demand response mechanism. Here, it is possible to use the conditions I found that a location should fulfill to make it optimal to use Bitcoin mining as a demand response. These conditions are shown in chapter 5.3.1.

As explained several times in this thesis, demand-side flexibility will be extremely important for maintaining stability in future electricity systems characterized by increasingly less supply-side flexibility because of more wind and solar. Bitcoin miners are very special energy consumers because of the technical characteristics related to their energy consumption. Never before have we had an energy-intensive industry with such flexibility. Therefore, I believe that Bitcoin miners provide positive externalities to electricity systems world-wide that are more difficult to measure than their energy consumption in TWh. But we definitely need more research on this.

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