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Sustainability Analysis of Cryptocurrencies Based on Projected Return on Investment and Environmental Impact

Olga Martynov

A Thesis in the Field of Sustainability and Environmental Management

for the Degree of Master of Liberal Arts in Extension Studies

Harvard University

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Abstract

Cutting edge technology behind cryptocurrency can revolutionize payment systems and transform the global economy. However, data shows cryptocurrencies major limitation, the significant energy consumption due to its high computing power requirement (De Vries, 2018). Moreover, increasing carbon dioxide emissions from Bitcoin mining alone could lead to a 2° C increase in global mean average temperatures within 30 years (CRS, 2019). The circumstances under which cryptocurrencies' evolution could be beneficial, or scenarios when it becomes a dramatic burden on society, is needed. This research aims to estimate cryptocurrencies' benefits by comparing its market value against its electric costs and associated social and environmental externalities over a ten year time frame.

My research examined cryptocurrencies true profitability through cost-benefit analysis and evaluated its environmental footprint, utilizing a range of scenarios and various models. To address my research questions, I tested two hypotheses. First, if cryptocurrencies' adoption rate follows the broadly used technologies growth pattern scenario, then in ten years, cryptocurrency's mining will require more electricity than consumed by the entire United States in 2018. Secondly, if the penetration of renewable energy into the electricity supply mix used by mining remains at current levels, I project that cryptocurrencies' fossil fuels consumption growth will lead to carbon dioxide emissions reaching 2018 United States CO2 emissions mark (5,269 MMmt) (EIA, 2019).

To address my research questions and hypotheses, two main research methods are used: cost benefit analysis and environmental footprint assessment. I developed a valuation framework utilizing a range of scenarios and various models to define the circumstances under which cryptocurrency evolution could be beneficiary or the opposite, the scenarios when it becomes a dramatic burden. I used a cost benefit analysis for comparing cryptocurrency's economic value against cryptocurrency's cost of mining, considering both economic and environmental costs, over a ten-year period.

The findings of this study showed that by 2028, the amount of cryptocurrencies market value needed to support economic activities would expand from current $240 billion to a range between $2.4 trillion to $2.9 trillion. The rising electricity requirements to produce cryptocurrencies could lead to likely electricity consumption of 293TWh (equivalent to 1 % of US energy consumed in 2018). This electricity consumption level would generate electricity costs ranging between $23 to $57 billion per year and carbon emissions ranging between 53 to 63.6 MtCO2.

The research results do not suggest that cryptocurrency is "burning down the planet", but the negative externalities identified in the research should be considered. For example, the results illustrate a scenario where each $1 of cryptocurrency coin value created would be responsible for $0.66 in health and climate damages. The externalities discussed in this study can be valuable for the development of standards around disclosure practices and in setting the right rules concerning adoption of blockchain and encrypted currencies.

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Chapter I

Introduction

Over the past few years cryptocurrencies have become a topic of research and debate (De Vries, 2018). Cryptocurrency is a relatively new combination of cryptology and currency in finance and is becoming more frequently used worldwide (Li et al., 2018). The early adoption of its technology as well as accelerated growth has raised many arguments in recent years. Public opinion is divided between praising benefits of cryptocurrency's financial capabilities, and claiming that the eventual impact of increasing carbon dioxide emissions from Bitcoin mining alone could lead to a two degree increase in global temperatures, should Bitcoin eventually replace other cashless transactions (Mora et al., 2018).

Cryptocurrency's exponential growth trajectory paired with its high energy-dependent production systems, like the commonly used "Proof-of-Work" (PoW) scheme, creates electricity usage problems currently and environmental dangers in the future. PoW refers to the process by which computers mining Bitcoin prove the data in each Bitcoin block; computers do this to define a math problem calculation in order to create a new group of trustless transactions on the distributed ledger (Kugler, 2018). However, according to "International Energy Agency's" (IEA) energy projections, by 2040, the global energy supply mix will shift from being currently dominated by fossil fuels to renewable energy (IEA, 2018). Therefore, projected changes to the global energy sources available for cryptocurrency production and its environmental footprint should be considered in this breakthrough technology value assessment.

Research Significance and Objectives

This research was intended to assess the sustainability of cryptocurrency as an asset and define if a shift to clean energy development will occur fast enough to keep up with cryptocurrency's exponential growth. I evaluated the potential evolution of cryptocurrency's energy consumption growth in correlation with the evolution of energy sources available for cryptocurrency's production in different geographical locations. My research assessed various scenarios of energy source changes in those locations to define under which scenario energy growth pattern towards renewables will suffice cryptocurrencies' energy usage and result in a sustainable economic and environmental value generation of the crypto asset. The research defined the circumstances under which cryptocurrency evolution can be regarded as 21st century growth opportunity or its opposite: the scenarios when it becomes a dramatic burden to the environment and society.

This assessment resulted in a calculation of cryptocurrencies' environmental footprint based on different scenarios of future electricity consumption levels and available energy supply mix. In addition to that, the research assessed potential alternatives to the commonly used Proof-of-Work mining scheme with smaller ecological footprints and similar technological advancement. This study could be useful for the next generation of cryptocurrencies and might help to model the sustainable development of cryptocurrencies that simultaneously maximize economic and environmental benefits.

My main objective was to assess the ten-year projections of cryptocurrencies' electricity consumption levels and associated electricity cost against cryptocurrencies' market capitalization value. This assessment was based on the predicted growth trends

and energy sector development scenarios. I also aim to define a wide range of scenarios of cryptocurrency electricity consumption based on different sets of assumptions of global changes to the energy source mix and different scenarios for the locations of crypto mining facilities.

My secondary objective was to explore consequences of cryptocurrencies' environmental footprint based on the projected changes to the energy supply mix in ten-year period and identified alternative crypto mining protocols that could be used in cryptocurrencies' production with minimal environmental footprint.

Background

Technology advancement can lead to revolutionizing payment systems and trigger development of new types of financial products. Cutting edge technology behind cryptocurrency complicates its asset class identification, as it is nothing like stocks or bonds (Brown, 2017). For accurate asset evaluation, it is critical to define under what asset class it falls, and if it can be categorized as money. Money can be described as "any asset that is generally accepted for payment for goods or services, or for debt settlement… money fulfills four basic functions: medium of exchange, common measure of value, standard of value and store of value," (Kubát, 2015, p. 6). There are four types of money recognized by economists: commodity, fiduciary, commercial bank, and fiat money. Most modern monetary systems are based on fiat money, known as paper money or coins (Fiat Money, 2018). On the other hand, the credit card, which is a highly used medium of payment, is not considered a form of money. Rather, a credit card is considered as just a medium to take a loan, but is not legal tender itself (Money, 2019).

What Is Cryptocurrency?

Based on the existing definition of money, how do we define and classify cryptocurrency? “Cryptocurrency can be thought of as a digital asset that is constructed to function as a medium of exchange, premised on the technology of cryptography, to secure the transactional flow, as well as to control the creation of additional units of the currency,” (Chohan, 2017, p.1). Accordingly, we can consider that cryptocurrency also fulfills some features described as money as it is regarded as a medium of value exchange; however, it represents a decentralized new currency that is beyond the control of any government or third party, like a bank (Kubát, 2015). As an entirely new asset class, consensus around valuation methodology is still evolving (Dowlat, 2018). Furthermore, cryptocurrencies are an “area of heightened pecuniary, numismatic, technological, and investment interest, and yet a comprehensive understanding of their theories and foundations is still left wanting among many practitioners and stakeholders,” (Chohan, 2017, p.1).

Cryptocurrencies’ Expansion

Many cryptocurrencies were created in recent years, and the most valuable based on market capitalization are Bitcoin, Ripple, Ethereum, Litecoin, and Monero. This movement all started with Bitcoin, introduced in October 2008 as a new system for electronic transaction. As of February 10, 2020, Bitcoin represents around 63% of cryptocurrency’s market capitalization (Coin Market, 2020). Since Bitcoin’s success, other cryptocurrencies have emerged: Litecoin was introduced on April 2013, followed by Ripple on August 2013, Monero on May 2014 and then Ethereum on August 2015

(Coin Market, 2019). As of February 2020, more than 5,000 different cryptocurrencies exist with the number of cryptocurrencies increasing daily (Coin Market, 2020).

The technology behind cryptocurrency allows a user to send 'currency' directly to others without going through a third party, like a bank. The advantages of a cryptocurrency, like Bitcoin, are widely appreciated as it can deliver quick payments worldwide, avoiding inflation caused by governments trying to solve their own problems, with a high level of transaction privacy (Kubát, 2015). The technology underlying these cryptocurrencies is blockchain. A blockchain is a digital distributed ledger that enables parties who may not otherwise trust one another to agree on the current ownership and distribution of assets in order to conduct new business (CRS, 2019).

However, some disadvantages of cryptocurrencies raise concerns, including its volatility and high resource consumption for coin creation and encryption. For example, the cryptocurrency Bitcoin secures its network through an energy intensive PoW scheme. Data shows that electricity usage to mine Bitcoin, the process of generating Bitcoins, is close to the electricity consumption by a medium-sized country (O'Dwyer & Malone, 2014), like Ireland (3.1 GW per year), and could reach as much consumption as Austria (8.2 GW per year) in the near future (IEA, 2017). In comparison to the mineral mining industry, it is estimated that crypto mining consumes more energy than mineral mining to produce an equivalent market value. For example, the top four by market capitalization cryptocurrencies, Bitcoin, Ethereum, Litecoin and Monero, consumed an average of 17, 7, 7 and 14 Megajoules (MJ) to generate one US$; comparatively, conventional mining of copper, gold, platinum and rare earth oxides consumed 4, 5, 7 and 9 MJ to generate one US$ (Krause & Tolaymat, 2018).

According to Kugler (2018), this process of generating Bitcoins is where the energy problem arises. The PoW scheme requires guessing the solution to an equation, which uses a great deal of computing power, and consequently, electricity. Therefore, cryptocurrency production using PoW protocol comes with a high environmental cost. However, there are several other alternative protocols known as consensus mechanism algorithms that are used by cryptocurrency networks and work on different principles. Twenty-one percent of top ranked cryptocurrencies by market cap (e.g. Bitcoin, Litecoin, Monero) use the PoW scheme (Figure 1) and this drives a focus on PoW protocol implications for energy usage and related greenhouse gas (GHG) emissions (Hays & Valek, 2018). Nevertheless, other consensus algorithm alternatives currently used or being developed need to be assessed to identify the most likely scenarios of consensus mechanisms development and utilization in ten years.

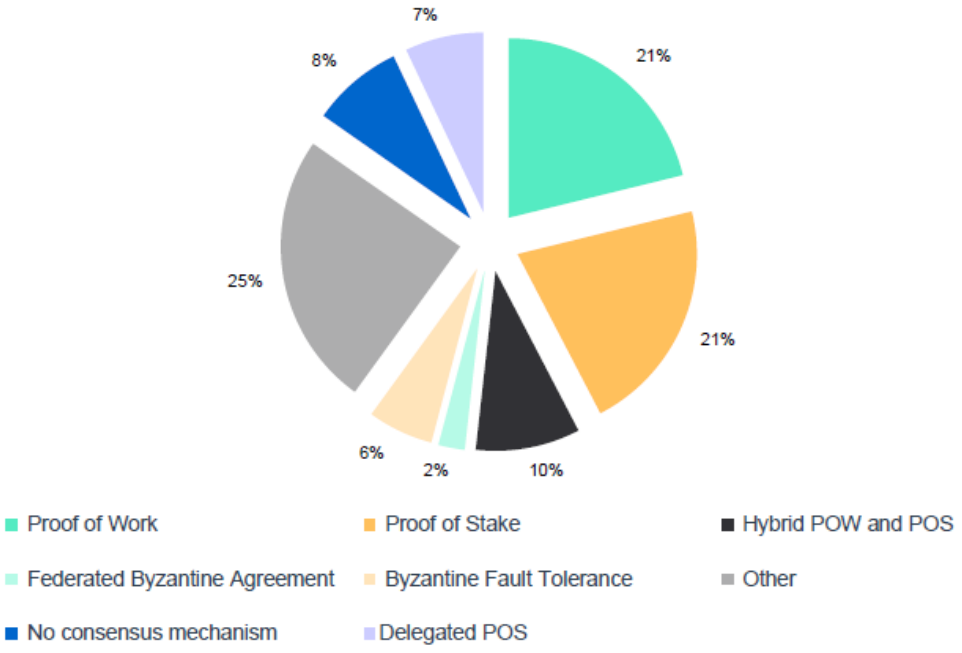


Figure 1. Top 100 cryptocurrencies by consensus mechanism (Hays & Valek, 2018).

Cryptocurrencies' Value and Production Cost Assessment

In 2017, the first global cryptocurrency benchmarking study presented a comprehensive picture of the cryptocurrency industry and "how cryptocurrencies are being used, stored, transacted and mined," (Hileman & Rauchs, 2017). In February 2017, Bitcoin and Ethereum Energy consumption indexes were created to track estimated global mining revenues and costs, electricity consumption levels, and estimated average carbon footprint per transaction (Digiconomist, 2020). Right now, Digiconomist (2020, p. 1, a self-described "platform that provides in-depth analysis, opinions, and discussions with regard to Bitcoin and other cryptocurrencies … on a voluntary, best-effort basis", estimates that Bitcoin mining accounts for 0.33% of the world's annual electricity consumption and the mining of a single bitcoin block consumes enough electricity to power more than 22 U.S. homes for a full day (Digiconomist, 2020, Kugler, 2018). This statistic triggered a need to identify cryptocurrency value formation and cost of production, and multiple studies were conducted to explore and define a well-fitting framework for this new asset.

Value formation. There is an emerging academic literature regarding cryptocurrencies, with most emphasis surrounding Bitcoin. Much of the economic study undertaken has attempted to address the "moneyness" of Bitcoin or whether it is more analogous to a fiat versus commodity money, like a "digital gold" (Hayes, 2015). But cryptocurrencies are different from other asset types as they are regarded as digital currencies with value within the network. Cryptocurrencies' market capitalization is calculated as number of coins multiplied by the trading price (Carey & Gunduz, 2018). Total cryptocurrency

market cap is assessed at $283 billion as of February 10, 2020 (CoinMarketCap, 2020). Bitcoin itself represents 63% ($179 billion) of total market cap.

In August 2018 Bloomberg published a study that expands on cryptoassets valuation, using three major models: top down, peer-based and bottom-up (Dowlat, 2018). Dowlat calculated estimated market capitalization using 2050 estimated supply using respective network inflation schedules. Dowlat concluded that the amount of cryptoasset market value needed to support economic activities will expand from 2017's $120 billion to $3.6 trillion by 2028 (Figure 2). Dowlat's (2018) valuation of the assets future value was based on multiple assumptions and was run under various scenarios and models. However, the study lacked research material supporting fluctuations associated with network operation, technical modifications or market risk. The Dowlat study can be used as a fundamental valuation technique, but additional quantitative analysis of network and technology trend-based models is needed to arrive at plausible valuation (Dowlat, 2018).

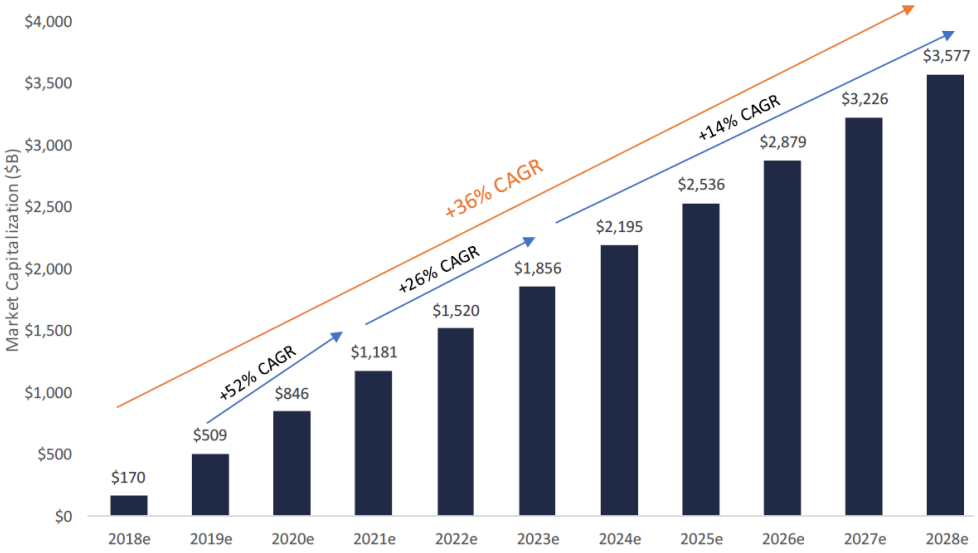


Figure 2. Estimated cryptoasset market capitalization over time (Dowlat, 2018).

Cryptocurrency's cost of production. Cryptocurrency mining is considered a big part of its production cost as "mining" means checking all monetary transactions on a peer-to-peer network within the Internet, which in turn create cryptocurrency, like Bitcoin, as a reward (O'Dwyer & Malone, 2014). A cryptocurrency system requires powerful hardware. Miners play a crucial role as they are responsible for grouping unconfirmed transactions into new blocks and adding them to the global ledger, which is called the "blockchain" (Hileman & Rauchs, 2017). Mining has grown from a simple hobby performed by early adopters on ordinary PCs into a capital-intensive industry that uses custom hardware equipment and features a specialized value chain (Hileman & Rauchs, 2017). Taking Bitcoin as an example, multiple studies agree that Bitcoin mining's two major factors are the hash rate of hardware and the cost of running this hardware (O'Dwyer & Malone, 2014). The electricity consumption required for equipment usage in cryptocurrency mining is major due to the mining machines' activities, cooling requirements, and data storage. However, the electricity cost of discovering one Bitcoin block varies significantly depending on the type and efficiency of the hardware used (Table 1).

Table 1. Examples of Bitcoin mining devices and associated energy costs (O'Dwyer & Malone, 2014).

Name	Type	Hash Rate R (Mhash/s)	Power Use P (W)	Energy Efficiency $\mathcal{E}$ (Mhash/J)	Cost ($)	Reference
Core i7 950	CPU	18.9	150	0.126	350	[8, 9]
Atom N450	CPU	1.6	6.5	0.31	169	[10, 9]
Sony Playstation 3	CELL	21.0	60	0.35	296	[11, 9]
ATI 4850	GPU	101.0	110	0.918	45	[12, 9]
ATI 5770	GPU	214.5	108	1.95	80	[13, 9]
Digilent Nexys 2 500K	FPGA	5.0	5	1	189	[14, 9]
Monarch BPU 600 C	ASIC	600000.0	350	1714	2196	[15, 9]
Block Erupter Sapphire	ASIC	333.0	2.55	130	34.99	[16, 9]

In August 2018, PWC Netherlands completed a peer review to outline various current methods being used to determine the current and future electricity consumption of the Bitcoin network (De Vries, 2018). Similar to the conclusions drawn from O'Dwyer & Malone's (2014) study, De Vries found that estimating the energy consumption of the Bitcoin network using efficiency for different hardware was a common approach for years. Yet different types of hardware machines and cooling requirements should be considered while minor costs such as maintenance should be ignored.

Hileman & Rauchs' (2017) study of 48 miners observed that a majority of the total Bitcoin network hash rate originates from mining machines clustered together in mining facilities, with eleven of them estimated to contribute more than half of the global Bitcoin network hash rate. De Vries (2018, p.2) reports that "these facilities are likely to have more power expenditures… with each of the machines generating as much heat as a portable heater, the additional electricity expenditure to simply get rid of all this heat can potentially be significant, depending on factors such as climate and chosen cooling technology." Based on these findings, De Vries (2018) concluded that the Bitcoin process is extremely energy-hungry by design. Current miner production estimates suggest that with the Bitcoin network processing just 200,000 transactions per day, the average electricity consumed per transaction equals at least 300 kWh and could exceed 900 kWh per transaction by the end of 2018 (De Vries, 2018). This means that Bitcoin could reach annual consumption of 7.67 GW in the future, making it comparable with countries such as Austria (De Vries, 2018).

Other cryptocurrencies that are structured similarly to Bitcoin are also significantly dependent on energy usage for mining (Kugler, 2018). In November 2018,

scientists from Hunan University in China performed an experimental case study of global electricity consumption of Monero cryptocurrency mining (Li et al., 2018). The study compared experiments on the mining efficiency of nine kinds of cryptocurrencies. The selected cryptocurrencies excluded Bitcoin, but represented ten different algorithms, and performed statistical analysis of data to derive estimated global electricity consumption of the Monero mining activity and associated carbon emissions in China. Based on the study assumptions and assessed variables, these researchers concluded that Monero mining in China may result in at least 19.12-19.42 thousand tons of carbon dioxide, considering a carbon intensity of 0.63-0.64 kg CO2/kWh in China (Li et al., 2018).

Li et al.'s (2018) study lacked a clear explanation of the method used for cryptocurrency sample size and subject selection. However, the study clearly indicated three main reasons that support selecting Monero cryptocurrency as a case study. The study concluded that the main variable of mining efficiency depends on the hashing algorithm. Furthermore, the study showed that hash rate mainly comes from mining pools in the United States, Europe, and Asia with largest mining pool servers located in China and America.

While most reports (e.g., O'Dwyer & Malone, 2014; De Vries, 2018; Li et al., 2018) suggest that the hashing algorithm, hash rate of hardware, and the cost of running this hardware are the key variables, consensus has not been reached on all the variables to be considered. There is still uncertainty between multiple papers reviewing cryptocurrency's cost of production. Further analysis of the key variables is needed to

determine whether the mining pool locations will have a significant impact on its overall cost.

Cryptocurrencies' Energy Dependencies and Energy Outlook

Based on PWC's projected growth trajectory, energy dependency is the key variable of cryptocurrencies' value assessment. Fossil fuels such as coal, oil, and gas dominate current energy systems, which produce carbon dioxide and other greenhouse gases; these gases are the fundamental drivers of global climate change (Ritchie & Roser, 2018). Energy systems result in huge environmental impact; a significant transition in world's energy sources is needed. Therefore, in terms of the availability of low-carbon energy resources, the evolution of energy supply will have a fundamental impact on cryptocurrencies' economic and environmental value.

Vaclav Smil's (2016) key point on energy transition is that shifts in energy systems have historically been very slow. Furthermore, this challenge needs to be considered in the future value assessment of cryptocurrencies' economic advantages to its environmental impact. The recent IEA's 2018 World Energy Outlook report explored future energy sector trends based on current data. This report also demonstrated what different policy choices might mean for the energy sector by 2040. IEA's forecast is based on three scenarios: current policies, new policies, and sustainable development. The report estimates that the global electricity generation will increase by some 60% (15,000 TWh) between 2017 and 2040 in the New Policies Scenario. For example, fossil fuels would remain as the major source for electricity generation, but their share would fall from around two-thirds today to under 50% by 2040 (Table 2) (IEA, 2018). The

report further highlighted a major shift in energy demand that is occurring from both advanced to developing economies. Nearly 90% of the growth in electricity demand occurs in developing economies, with demand growing fastest in India (IEA, 2018). The report further estimated that the changes in low-carbon generation and fossil fuel demand will depend on the region, and stipulated that demand growth in advanced economies and China will be met by low-carbon technologies and gas. In contrast, India and other developing Asia were projected to mobilize all fuels and technologies (IEA, 2018). Therefore, crypto "mining" factories' locations will play a key role in cryptocurrencies' future value assessment, as its electricity cost and environmental footprint directly correlates with energy sources available in different parts of the world.

Table 2. World electricity generation by fuel and scenario in TWh (IEA, 2018).

			New Policies		Current Policies		Sustainable Development	
	2000	2017	2025	2040	2025	2040	2025	2040
Coal	6 001	9 858	9 896	10 335	10 694	13 910	7 193	1 982
Oil	1 212	940	763	527	779	610	605	197
Gas	2 747	5 855	6 829	9 071	7 072	10 295	6 810	5 358
Nuclear	2 591	2 637	3 089	3 726	3 079	3 648	3 303	4 960
Hydro	2 618	4 109	4 821	6 179	4 801	5 973	5 012	6 990
Wind and solar PV	32	1 519	3 766	8 529	3 485	6 635	4 647	14 139
Other renewables	217	722	1 057	2 044	1 031	1 653	1 259	3 456
Total generation	15 441	25 679	30 253	40 443	30 971	42 755	28 859	37 114
Electricity demand	*13 156*	*22 209*	*26 417*	*35 526*	*26 950*	*37 258*	*25 336*	*33 176*

Notes: TWh = terawatt-hours. Electricity demand equals total generation minus own use (for generation) and transmission and distribution losses. Total generation includes other sources.

Mining Facilities' Location

Considering the geographic distribution of the major mining areas, nearly three-quarters of all major mining pools are based in just two countries: 58% of the mining pools with greater than 1% of the total Bitcoin hash rate are based in China, followed by

16% in the United States (Hileman & Rauchs, 2017). Changes to the cryptocurrency's mining facilities will have a material impact on its cost of operations and environmental footprint. Determining where to establish a cryptocurrency mining facility is generally based on three key factors: "Miners need to have access to low-cost electricity to run their operations profitably, they need to have a sufficiently fast internet connection to quickly receive and broadcast data with other nodes on the network, and mining equipment must be kept from overheating to function optimally, which is why locations that have low temperature zones offer substantial advantages as cooling costs can be kept low," (Hileman & Rauchs, 2017).

The cryptocurrency mining map (Figure 3) shows that mining facilities are mainly concentrated in locations where most of the key drivers discussed above are satisfied. However, publicly available literature indicates the trend of miners leaving China and shifting their operations to certain regions of Scandinavia, Russia, Canada, and the United States, where the combination of cheap abundant electricity, friendlier regulation, fast internet connections and, to a lesser degree, cooler climates can be attained (Bendiksen, Gibbons, & Lim, 2018). The mining facility location dictates the energy mix used for mining, and therefore the range of alternative scenarios of future major mining pool locations need to be assessed.

In summary, cryptocurrency mining and blockchain technology are promising, but their influence on energy conservation and sustainable development should be further studied. The existing literature of cryptocurrencies can be grouped into two categories. The studies in the first category include technologies that support digital currencies and the second category characterizes cryptocurrencies through various financial analysis (Li

et al., 2018). Data are available on cryptocurrencies' historical trend and projections are available on its future value. However, currently no research is available on the electricity consumption of cryptocurrencies' and greenhouse gas emissions levels based on the predicted future energy sources used in cryptocurrency production in different regions of the world. This assessment, which considers different scenarios of cryptocurrency's rate of adoption and technology advancement in parallel with evolution of clean energy sources, defines if cryptocurrency can be supplied by lower cost renewable energy rather than by use of the fossil fuels.

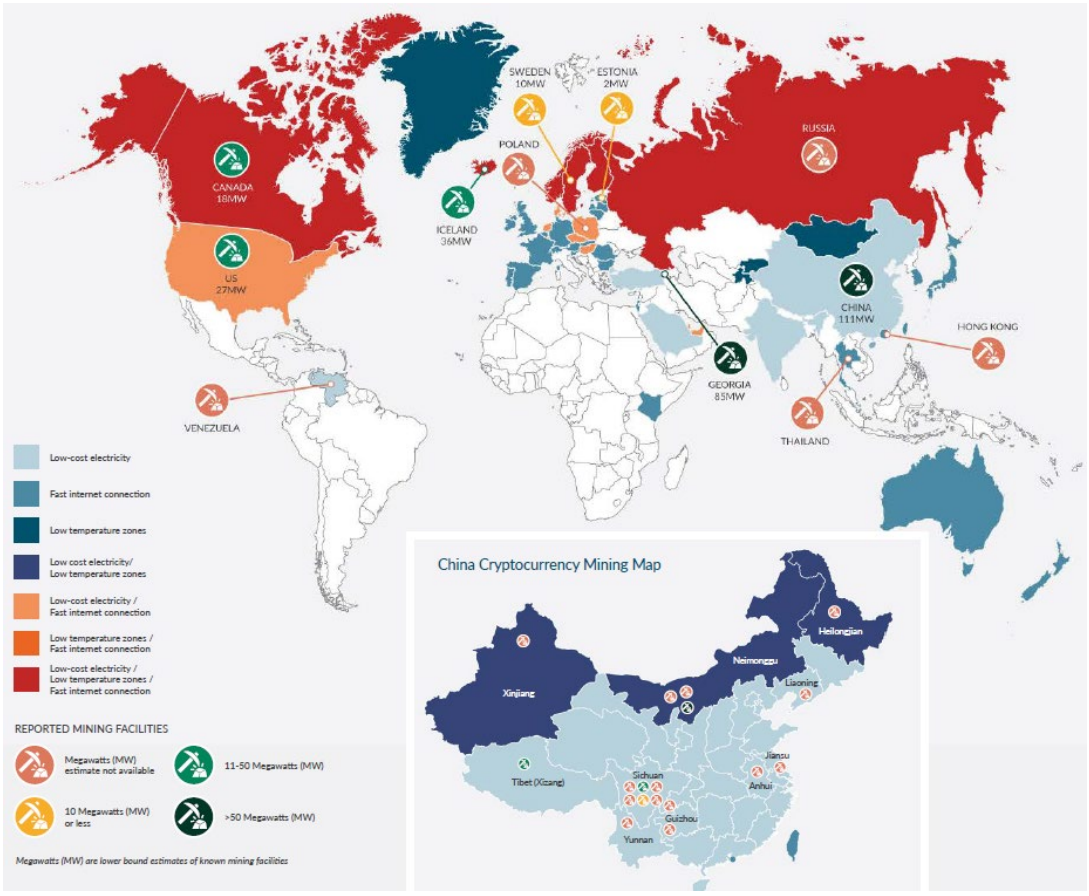


Figure 3. Global cryptocurrency mining map (Hileman & Rauchs, 2017)

Research Questions, Hypotheses and Specific Aims

The proposed research questions and hypotheses focus on scenario analysis of cryptocurrency profitability, the return on investment, and its environmental footprint. My primary research questions are: Considering current cryptocurrencies' trends and prices for electricity, what will be cryptocurrencies' profitability in ten years? What are the possible changes that will impact the cost of cryptocurrencies' production? How will changes to the mix of energy sources impact its environmental footprint and cost of crypto production in ten years? I answered these questions by testing the following hypotheses. In order to test profitability of cryptocurrency I broke down the primary hypothesis into two sections. Hypothesis 1a will test the prediction of cryptocurrency electricity consumption levels and hypothesis 1b will then test cryptocurrency energy costs compared to its market value.

Hypothesis 1a: Based on the baseline scenario of cryptocurrency adoption rate, in a ten-year period, cryptocurrencies' production and data storage will require more electricity than used by the entire United States in 2018.

Hypothesis 1b: Based on this growth trajectory and assuming current policy energy source evolution and the baseline scenario of mining facility locations, cryptocurrencies' value (market cap) will be less than the cost of the energy required to generate it over a ten-year period.

My secondary research questions focus on the environmental footprint of cryptocurrency production: In ten years, how will clean energy development and the use of low carbon sources of energy offset cryptocurrencies rising demand for energy, which is currently dominated by fossil fuels? How will the application of different crypto

mining protocols impact environmental footprint associated with cryptocurrencies' production? Will crypto mining use less electricity as it becomes more efficient to mine or will its production continue to operate at the same or even greater energy levels until the supply reaches the capacity? I addressed these questions by testing the following hypothesis:

Hypothesis 2: Rapid growth in the cryptocurrency industry will lead to a significant increase in greenhouse gas emissions levels and other air pollutants in the atmosphere. I predict that in ten years, climate damages and related health implications just from cryptocurrency industry will be equivalent to the climate damages from the United States CO2 emissions levels in 2018.

Specific Aims

To complete this research, I have:

1. Calculated the expected value of the cryptocurrencies (market capitalization) versus estimated electricity consumption costs associated with its production, comparing different scenarios of cryptocurrency evolution and energy development.
2. Assessed the global evolution of cryptocurrencies' production by geographical locations.
3. Identified projected changes to the available energy sources in those geographical locations and determined if a move away from fossil-fuel based electricity generation to sustainable alternatives would be possible for crypto mining.

4. Created an environmental footprint assessment model to define climate impacts from the cryptocurrency industry, including social costs and damage to human health.
5. Analyzed different crypto mining protocol alternatives that can be used for cryptocurrency production, and determined which alternative has minimal environmental footprint.

Chapter II

Methods

To address the research questions and hypotheses, two main research methods were used: cost benefit analysis and environmental footprint assessment. A cost benefit analysis (CBA) framework was utilized to compare the benefits and costs of cryptocurrency technology by defining cryptocurrency fair value and subtracting all the costs associated with its production. CBA methodology was selected as it considers estimated costs and benefits discounted at the appropriate rate to evaluate cryptocurrencies over a period of years. The time value of money technique was then applied to find cryptocurrency's present value. Limitations of the analysis will be inclusive of the definition of the discount rates. Analysis was performed by comparing cryptocurrencies' economic value against cryptocurrencies' cost of production; economic and environmental costs over a ten-year period were also considered. Environmental footprint analysis was performed to assess cryptocurrencies' emissions footprint based on current and projected energy sources and associated health implications.

Cost Benefit Analysis

Cryptocurrencies' economic valuation was performed over a ten- year period by comparing 2018 cryptocurrencies' fair market value to 2028 discounted present value in a spreadsheet model. A ten-year period was selected for future value assessment based on ten-year historical data available on Bitcoin since its inception in 2008. Five core valuation parameters with multiple independent and dependent variables and a wide range of scenarios were assessed for cryptocurrency value forecasts. Key variables

included in the model were cryptocurrency market-cap based on cryptocurrency adoption rate, cryptocurrency cost, global energy mix changes, major mining factories location, and mining protocol (consensus algorithm) alternatives. Variables and scenario selection were assessed as part of the research based on the assumptions derived from research literature examination.

Cryptocurrencies' value assessment. Unlike the market valuation of an asset, standard valuation models do not work for cryptocurrencies as they do not fall under any traditional asset category, like stocks, bonds, or property. Predicting the ten-year projected value of cryptocurrencies therefore requires a new monetary model that considers multiple factors in crypto asset valuation, such as market expectations, cryptocurrencies' mining and hash rate, money supply, and velocity. Financial modeling analysis determined which variable were the most important in cryptocurrencies' value assessment. Multiple scenarios were derived from the value assessment model and results were tested with different sensitivity analyses; simulations were performed to predict the expected value, given a range of inputs and factors.

To address hypothesis 1a, I relied on data from a recent peer-reviewed study, which estimates the amount of cryptoasset market value needed to support economic activities by 2028. Then I applied the findings of this study to calculate the ten-year projected value of the entire cryptocurrency pool (market value needed as of 2028 and the annual market capitalization yield for 2018). These findings were then compared to the estimated electricity consumption costs associated with crypto currency production across the range of scenarios and relevant upper and lower bound of projections.

Dowlat's (2018) study was used as a conceptual framework for cryptoasset valuation. The study provided top down cryptoasset valuation using the quantity theory of money to deduce the value of cryptoassets needed to support a forecasted economy. As an analyst from *The Satis Group* put it:

> To estimate the size of the economy supported by cryptoassets, a ten-year model for use cases most relevant to the strengths of particular networks was built and penetration rate, or the percentage of the economy's value that will be traded using cryptocurrencies vs. fiat currencies was estimated. This addressable market was then divided by the coin's velocity to arrive at the market capitalization of cryptocurrencies. The market capitalization attributed to particular coin was further divided by its supply to arrive at the market capitalization per coin, i.e. its price (Dowlat, 2018, p. 3).

Dowlat's study calculated the cryptocurrency needed to support economic activities in ten years rather than actual forecast of cryptoasset value based on the historical trend. Therefore, I validated Dowlat projections based on the historical trend forecast. I created a five-year forecast based on existing cryptoasset five year historical trend and then compared the results to Dowlat's model five-year projection, adjusted by 25% due to previously identified variance to actuals. To calculate net present value of 2023 yield from cryptoassets, I obtained the five-year historical trend of market capitalization value of cryptocurrencies (quarterly trend from 2015 through 2018 and average daily price base through 2018 year due to the inflationary nature of the crypto asset).

Considering the significant data fluctuations over a five-year historical period, linear regression was used to create an exponential smoothing forecast. This forecast was created by using MS Excel Forecast.ETS function as this algorithm smooth deviations in data trends by detecting seasonality patterns and confidence intervals. The confidence interval level was set at 95% to generate upper and lower confidence level and

seasonality was set at nine, representing the length of the seasonal pattern identified in the historical data.

Cryptocurrencies' energy consumption projections. Power usage of cryptocurrency was assessed following De Vries' (2018) approach on estimating the power consumption of the bitcoin network in combination with the Li et al.'s (2018) experimental case study of global electricity consumption of Monero cryptocurrency mining. To model electricity consumption forecast over ten years, first I needed to assess which cryptocurrencies' energy consumption levels are relevant to the study and what historical data is available. The top 30 largest cryptocurrencies by market capitalization represent approximately 93% of all cryptoasset market cap value, as of August 31, 2019 (CoinMarketCap, 2019). The top 30 cryptocurrencies are categorized by consensus mechanism in Table 3 and demonstrate that PoW is the leader as it represents 80% of top 30 altcoins and equates to 75% of total cryptocurrencies value. The PoW/ "Proof-of Stake" (POS) hybrid represents 9% of top 30 and 8% of total cryptoassets. All other consensus mechanism in aggregate represents 11% of total crypto currency value.

Table 3. Top 30 altcoins by consensus mechanism and market capitalization (CoinMarketCap, 2019).

30 Top Consensus Mechanism Categories	Market Cap (August 31st, 2019)	% of Top 30 total	% of total Crypto Currency
DPos	$4,038,005,006	2%	2%
Other	$19,094,882,088	8%	8%
PoS	$2,388,604,722	1%	1%
PoW	$187,167,176,317	80%	75%
PoW/PoS Hybrid	$20,750,218,900	9%	8%
Top 30 coins market cap	**$233,438,887,033**	**100%**	**93%**
Total Cryptocurrency market cap	**$250,164,249,757**		

However, based on the top 30 cryptocurrencies by market cap, Bitcoin, Ethereum and Ripple are the leaders and represented 86.4% of total cryptocurrency market cap as of August 31st, 2019 as shown in Table 4. These are also representative of different consensus mechanisms with PoW and PoS/PoW Hybrid being the most common consensus that propose solutions to the Byzantine Generals' Problem. But there are other consensus algorithms, like Ripple protocol consensus algorithm (RPCA), that reconcile which transactions are valid (Hays & Valek, 2018). Bitcoin makes 73.9% of total cryptoasset value, Ethereum contributes 7.8% and Ripple coin represent 4.7% of total cryptocurrency value.

Table 4. Top three altcoins by consensus mechanism and market cap (CoinMarketCap, 2019).

Coin by Category		Market Cap (August 31st, 2019)	% TOTAL Cryptocurrency
Ripple Protocol consensus algorithm (RPCA)			
Ripple	$	10,995,545,063	4.7%
Proof of Work (PoW)			
Bitcoin	$	172,530,675,547	73.9%
POW/POS Hybrid			
Ethereum	$	18,186,346,001	7.8%
Total	**$**	**201,712,566,611**	**86.4%**
Total Cryptocurrency market cap		**$250,164,249,757**	**100%**

Previous peer-reviewed studies validate that most altcoins share in common a Bitcoin lineage, and the majority of cryptocurrencies have the same set of built in variance, and the amount of computational power devoted to finding a 'coin' positively correlates to altcoin value, (Hayes, 2015). Based on this assumption and the above top 30 cryptocurrencies' analysis by market capitalization, I concluded that Bitcoin, Ethereum, and Ripple should be selected for the detailed analysis and then used as a basis of

cryptocurrency energy consumption projections in order to aggregate the full cryptocurrency population.

To obtain historical electricity consumption data for these three cryptocurrencies, I first obtained five year estimated energy consumption historical data. Data for Bitcoin is available from two most popular sources: Digiconomist Bitcoin Energy Consumption Index (Digiconomist) and Cambridge Bitcoin Electricity Consumption Index (CBECI). Per comparison of both methodologies on the estimates over a two-year period, both indexes agree that Bitcoin consumption increased by 800% over two years, regardless of standalone points per Figure 4 (Digiconomist, 2020). Therefore, I relied on CBECI historical data as the basis of my calculations, as this index represents peer-reviewed material, accredited by the University of Cambridge Centre for Alternative Finance.

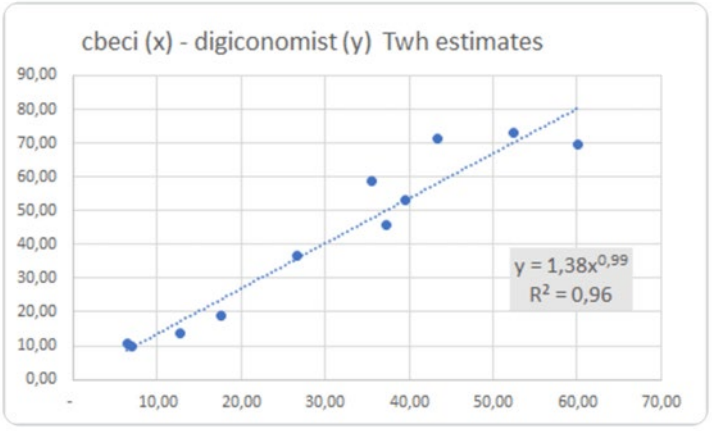


Figure 4. Bitcoin electricity consumption indexed comparison (Digiconomist, 2020).

I then obtained three year estimated consumption data for Ethereum, sourced from Digiconomist Ethereum energy consumption index, which has been designed with the same purpose, methods, and assumptions as the Bitcoin Energy Consumption Index (Digiconomist, 2020).

Lastly, I needed to obtain the historical data on Ripple energy consumption levels and estimate all other cryptocurrencies energy consumption levels based on the top three cryptocurrencies data. Ripple is a technology that is mainly known for its digital payment network and its own cryptocurrency "XRP" but instead of using the blockchain mining concept, Ripple uses a unique distributed consensus mechanism through a network of servers to validate transactions (Investopedia, 2019). "Ripple confirms transaction using selected validators and this decreases the energy requirement and significantly reduces speed, hence, transactions on Ripple would take only 4-6 seconds to confirm while Bitcoin transactions take around 15-25 minutes to confirm" (Febin, 2018, p 65). Therefore, Ripples' energy consumption is considered minimal comparing to POW or POS protocols. Based on the transaction confirmation time of Ripple vs Bitcoin, Ripple represents 0.42% of the time needed for Bitcoin to validate a transaction. By applying this % variable to the annual Bitcoin energy consumption levels over five years, I estimated Ripple's energy consumption at 0.26 TWh, as of August 2019.

To calculate top three cryptocurrencies' electricity consumption projections in ten years, data from 2015 to 2019 was used to construct a prediction model of electricity consumption by 2028. The exponential smoothing forecast MS Excel Forecast.ETS function was used, as this algorithm smooths deviations in data trends by detecting seasonality patterns and confidence intervals. To improve the prediction accuracy of electricity consumption in actual modeling, it was found that the data closer to the forecast period exerted more significant effects on prediction efforts (Li & Zhang, 2018). Therefore, to generate upper and lower confidence levels, the confidence interval level was set at 95%. Based on the historical trend, I identified the cyclicality of energy

consumption data. Therefore, average values were used to smooth out seasonal variations. The number of seasonal data point was set at nine, representing the length of the seasonal pattern identified in the historical data. The Figure 5 calculations demonstrate that total energy consumption forecast will exhibit a relatively stable rising trend in the following ten years and will reach nearly 235 TWh per year mark, with lower bound at 153 TWh and upper bound at 317TWh.

Based on the previous calculation per Table 5 above, the top three cryptocurrencies represent 86.4% of total cryptocurrency market cap as of August 31st, 2019. Thus, all other cryptocurrencies represent approximately 13.6% of the cryptoasset.

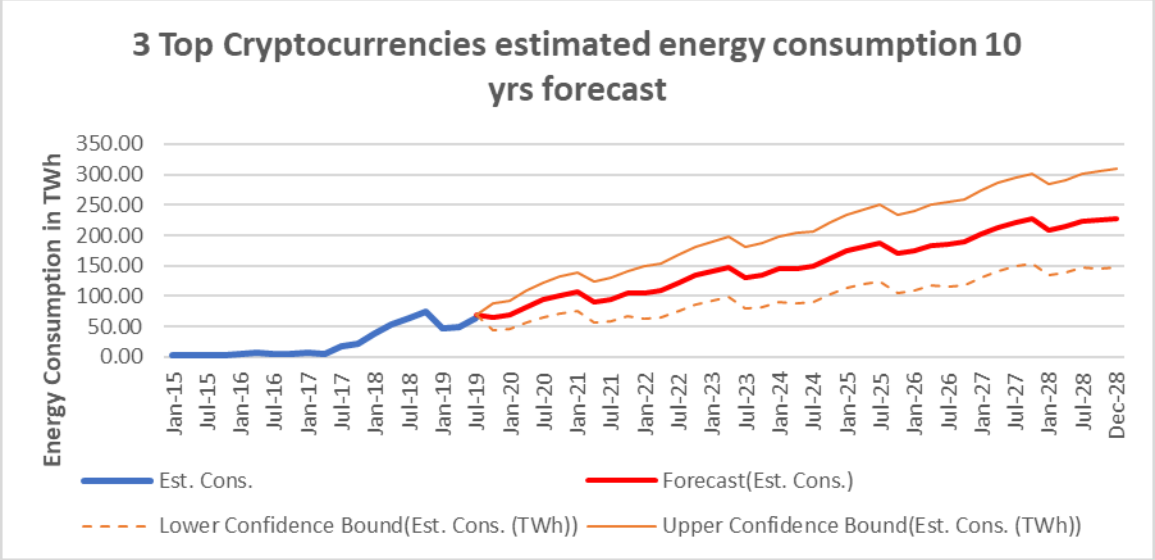


Figure 5. Energy consumption estimates of top 3 cryptocurrencies (in TWh).

By relying on the previously validated assumption of De Vries' (2018) study that cryptocurrencies' energy consumption is proportionate to its value creation, I assumed that each cryptocurrency's electricity consumption percentage of the total would be

proportionate to its market cap value. Therefore, if the top three cryptocurrencies (Bitcoin, Ethereum and Ripple) represent 86.4% of cryptocurrency market capitalization and consume approximately 69TWh (as of August 2019), I estimated that all other cryptocurrencies represent 13.6% of total consumption and consume 10.9 TWh. The total cryptocurrencies consumption was equal to approximately 79.9 TWh as of August 2019 (Figure 6).

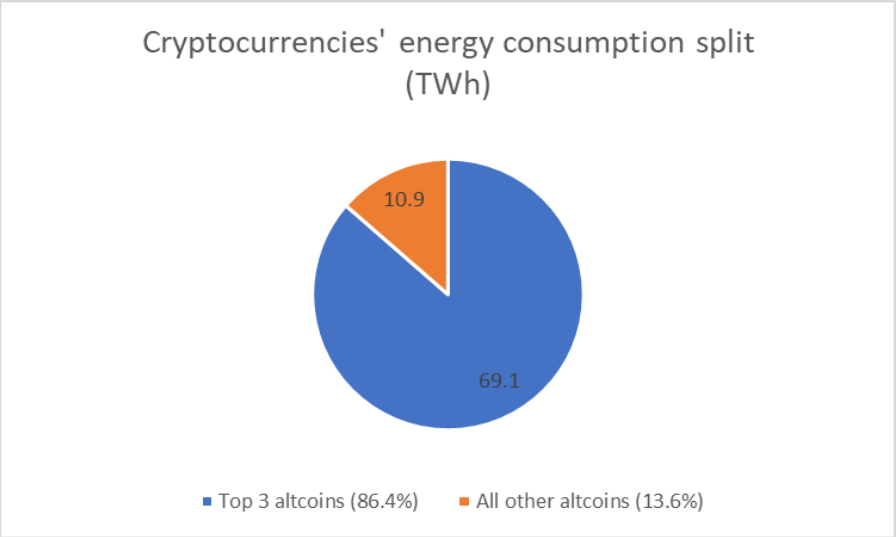


Figure 6. Cryptocurrencies energy consumption estimates (in TWh).

Given that the exact electricity consumption of cryptocurrencies cannot be determined due to the limitation of data transparency, a range of possibilities consisting of upper and lower bound estimates was examined. Considering a wide range of consumption estimates and assumptions used in this calculation, I applied CBECI's methodology to establish the lower bound estimate, which corresponds to the minimum total electricity expenditure based on the best case assumption that the most energy-efficient equipment and renewable energy sources are used. Per CBECI's methodology,

the upper bound estimated the maximum total electricity expenditure based on the worst-case assumption that the least energy-efficient hardware available on the market was used. The likely case estimate assumed that different hardware and energy sources were used rather than a single model (CBECI, 2019).

Assessment of Cryptocurrencies' Production by Geographical Locations

A cryptocurrency's production number changes daily, and was designed to be untraceable. To estimate cryptocurrencies' growth and related production by geographical locations, this research needed to consider multiple scenarios when estimating growth. However, relevant research data and statistical analysis of the data were available on Bitcoin and Ethereum, two highly disruptive cryptocurrencies. Using this historical data as a benchmark, a model was built and simulations were conducted; these were used to predict the expected values given a range of inputs and factors per financial forecasts and predict the market capitalization of global digital currencies.

Recent assessment (e.g., Hileman & Rauchs, 2017; Bendiksen, Gibbons, & Lim, 2018) of cryptocurrency's major mining pool location mix was considered as a baseline scenario of this research. A range of alternative scenarios of the future major mining pool locations was assessed as part of my research. A sustainable alternative was considered based on a shift to cool geographical areas with low cost electricity and high-speed internet connectivity. These scenarios were included as key variables in the cryptocurrency cost benefit analysis model. I assessed cryptocurrencies' growth in the different geographical locations over a ten-year time horizon through a combination of linear regressions and a simulation analysis.

*Cryptocurrencies' production cost assessmen*t. To address hypothesis 1b, I examined each cryptocurrency's energy costs compared to its market value. For that I first defined electricity costs applicable to cryptocurrencies and then calculated forecasted cryptocurrencies' production costs using energy consumption projections based on three scenarios.

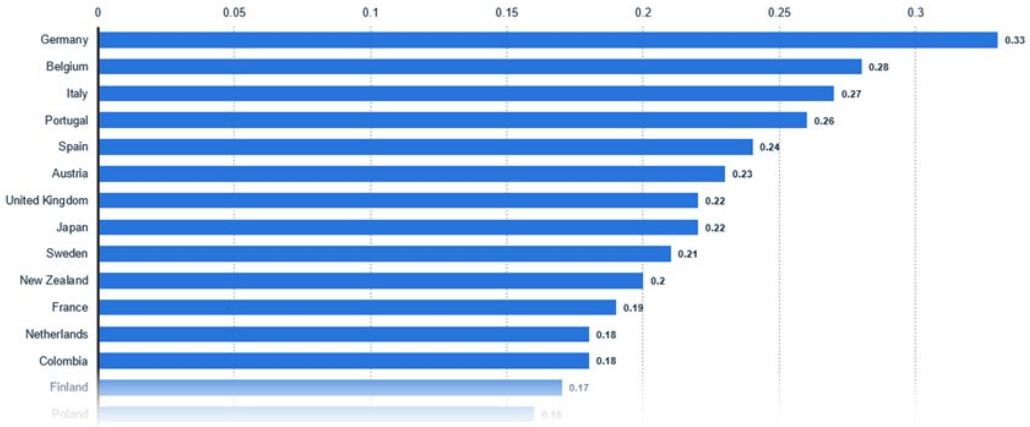


Figure 7. Global electricity prices in 2018, by select country in U.S. dollars per kilowatt hour by World Energy Council (Statista, 2019).

Global electricity pricing varies significantly by geography, and in 2018 ranged from $0.01 kWh in Argentina to $0.33 per kWh in Germany (Figure 7) (Statista, 2019). During 2018, the world average electricity pricing was estimated at $0.17/kWh. The majority of cryptocurrency mining currently happens in China and the United States. Most analysts anticipate a further shift towards Scandinavia, Canada and the U.S. (Li et al., 2018). The electricity outlook in the U.S. supports expected growth in generating energy from natural gas and renewables as illustrated in Figure 8. Based on the World Bank energy price index outlook to 2030, in ten years the overall electric cost is expected to reduce by circa 3% (Figure 9) (Statista, 2019).

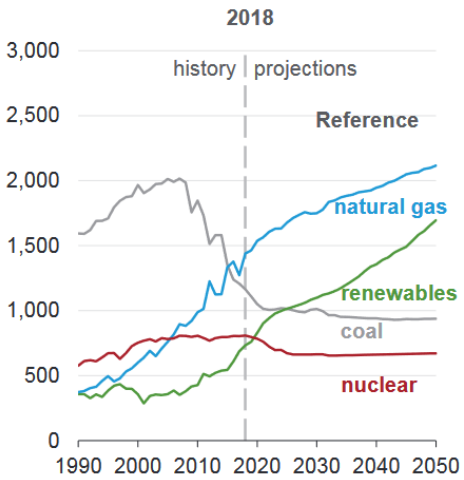


Figure 8. EIA's electricity generation from selected fuels in billion kWh (EIA, 2019).

For the purposes of this research, electricity pricing rate was calculated based on the projected average rate in the identified geographical locations (Hileman & Rauchs, 2017). Based on the average cost of electricity in Sweden, the United States, and China in 2018, I calculated the ten-year cryptocurrencies' pricing projections, equating to circa $0.13/kWh (similar levels as 2018 U.S. electricity pricing). Long term forecasts of electricity consumption may be unreliable or impractical as the average annual growth rate of electricity consumption is high and unstable (Li & Zhang, 2018). Therefore, sensitivity analysis was performed to assess the upper and lower bound projections of the electricity cost over a ten-year timeframe.

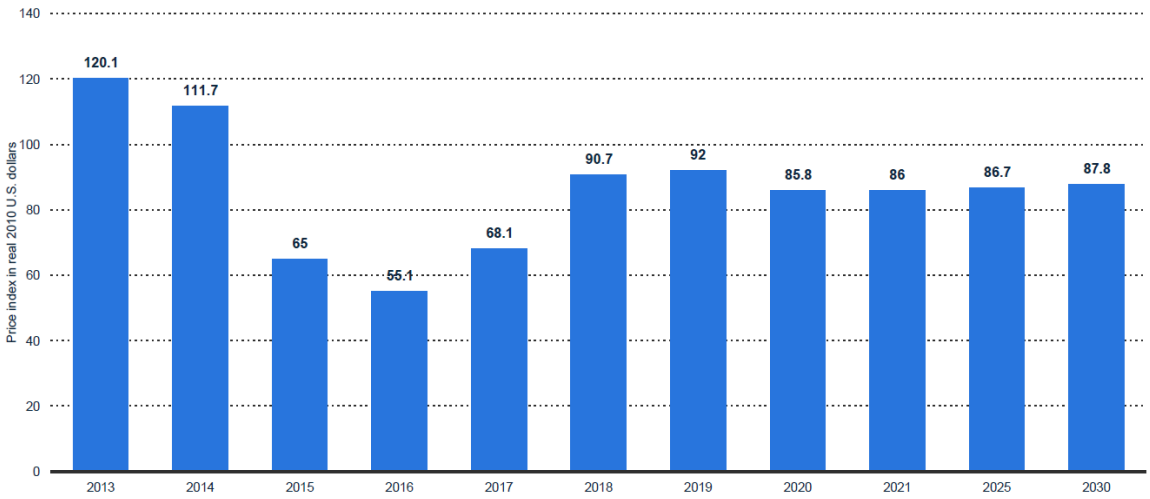


Figure 9. World Bank price index of energy worldwide from 2013 to 2030 in real 2010 US dollars (Statista, 2019).

Projected Changes to Global Energy Sources

The goal of the study was to compare the impacts of cryptocurrency production based on the current energy source to the impact from a projected energy source. To define ten-year energy source projections, I relied on the International Energy Agency's expertise. I also utilized data collected in the recent World Energy Outlook report, which provides a framework for what the future of global energy could look like based on different scenarios or pathways (IEA, 2018). To identify conservative energy projections of the global energy supply mix by 2030, I assessed different energy policy scenarios and related forecast of energy demands and suggested energy generation sources by region. IEA's three scenarios (current policies, new policies and sustainable development) were used to assess future energy source mix.

Environmental Footprint Assessment

To address the second hypothesis, I assessed the environmental footprint of cryptocurrencies based on current and projected electricity consumption levels. The environmental costs were monetized as the price of cryptocurrencies' digital footprint, with electricity consumption for currency mining and data storage based on "mining factories" location scenarios and related energy source mix scenarios, evaluating baseline year and ten-year projections. To perform cryptocurrencies' emissions assessment, energy consumption model outputs were used as inputs in modeling environmental footprint and associated human health damage. The scope included the assessment of the environmental impacts on air quality, and human health impacts were calculated with a world per capita normalization. The assessment of a wide range of scenarios on electricity consumption levels was based on the changes to the major mining pool locations and energy source mix used in the cryptocurrency's production and data storage. Based on the scenarios, CO2 per kwh electricity parameters were derived and GHG emissions were calculated.

Carbon emissions assessment. The fact that most mining facilities in Bitcoin's network, for example, are in regions (primarily in China) that rely heavily on coal-based power creates a bigger footprint (Digiconomist, 2020). As of the end of 2018, more than two-thirds of the current computing power was grouped by Chinese pools, followed by the 11% of pools registered in the EU (Stoll, Klaaßen & Gallersdörfer, 2019). U.S-based miners tend to join the European pool as the operation of mining pools is prohibited inside the United States (Stoll, Klaaßen & Gallersdörfer, 2019). Combining these insights

from pool server IPs with pool shares in terms of their regional origin, I allocated mining locations as 68% Asian, 17% European, and 15% North American (Stoll, Klaaßen & Gallersdörfer, 2019).

Determining the exact carbon impact of cryptocurrencies is challenging as it requires justifying assumptions on the location of miners and what powers it. First, I used MIT's methodology of calculating Bitcoin's annual carbon emissions, which determines the geographical footprint of mining activity based on the localization of IP addresses of the mining pools. This geographical footprint analysis is considered as the most accurate estimate of carbon emissions, as it is based on pool server IPs, miners' IP and device IP addresses and regional carbon intensity of electricity consumption (Stoll, Klaaßen & Gallersdörfer, 2019).

The calculation of Bitcoin's carbon footprint was based on 2018 total electricity consumption estimates and the geographical footprint, multiplied by the average and marginal emission factors of power generation. "Average emission factors represented the carbon intensity of the power generation resource mix, while marginal emission factors account for the carbon intensity of incremental load change," (Stoll, Klaaßen & Gallersdörfer, 2019, p 10).

Secondly, to translate other cryptocurrencies power consumption estimates into carbon emissions, I applied MIT's Bitcoin emissions results to estimate 2018's carbon emissions baseline range. I used the same methodology as in previous energy consumption calculations, assuming correlation of energy consumption to market capitalization. To determine the amount of carbon emitted in 2018, I multiplied power consumption estimates by average and marginal emissions factors of Bitcoin power

generation, using MIT's calculated Bitcoin CO2 emissions factor (weighted average of minimal and maximum range for likely case).

Thirdly, I developed three scenarios to create cryptocurrencies' carbon footprint ten-year outlook and to calculate a range of possible CO2 emissions and related health implications. Each scenario was based on a specific set of assumptions, supported by IEA's energy outlook projections, which were differentiated primarily by their underlying assumptions about the evolution of energy-related government policies (IEA, 2017).

Table 5. IEA's CO2 emissions scenario projections by regions (IEA, 2017).

	New Policy (NPS)			Current Policy (CPS)		Sustainable Development (SDS)	
Total Annual CO2 emissions (MtCO2)	2016	2030	% Change 16-30	2030	% Change 16-30	2030	% Change 16-30
World	32,072	34,259	6.8%	37,828	17.9%	25,146	-21.6%
N. America	5,819	5,432	-6.7%	5,844	0.4%	3,763	-35.3%
U.S.	4,837	4,491	-7.2%	4,809	-0.6%	2,986	-38.3%
Central & S. America	1,207	1,303	8.0%	1,415	17.2%	1,010	-16.3%
Europe	3,903	3,183	-18.4%	3,619	-7.3%	2,394	-38.7%
E.U.	3,121	2,384	-23.6%	2,725	-12.7%	1,816	-41.8%
Africa	1,164	1,447	24.3%	1,564	34.4%	1,159	-0.4%
Middle East	1,748	2,134	22.1%	2,262	29.4%	1,740	-0.5%
Russia	1,450	1,415	-2.4%	1,507	3.9%	1,170	-19.3%
Asia Pacific	15,137	17,282	14.2%	19,409	28.2%	12,346	-18.4%
China	8,973	9,112	1.5%	10,618	18.3%	6,319	-29.6%
India	2,214	3,717	67.9%	4,087	84.6%	2,798	26.4%
OECD	11,456	9,956	-13.1%	10,907	-4.8%	7,065	-38.3%
Non-OECD	19,424	22,785	17.3%	25,277	30.1%	16,974	-12.6%

The current policy scenario (CPS). This scenario considers no changes to the existing mining pool locations and emission levels; it does take into consideration the impact of governmental policies and measures that are firmly enshrined in legislation as of mid-2017, as defined in IEA's "current policy" emissions' outlook (IEA, 2017). To estimate amount of carbon emissions by 2028, I multiplied power consumption estimates (ranging from 196TWh to 390TWh) by 2018 baseline average and marginal emissions factors of

Bitcoin power generation, using MIT's CO2 emissions factors (weighted average of minimal and maximum range for likely case).

I believe that the application of this data is acceptable; the main point was to present a methodology that identified differences in CO2 emissions based on national energy mixes and the average amount of energy consumed to generate cryptoasset (Krause & Tolaymat, 2018). Secondly, to apply IEA's current policy emissions outlook, I have adjusted the calculation by a 17.9% increase, per Table 5, based on IEA's current policy world CO2 emissions anticipated change by 2030.

The new policies scenario (NPS). This scenario is based on IEA's central energy outlook scenario of "new policies." The scenario aims to provide the direction in which the latest policy ambitions could take the energy sector, considering the effects of the existing policies, as well official targets, such as the Nationally Determined Contributions of the Paris Agreement (IEA, 2017). To estimate the amount of carbon emissions by 2028 under NPS, I multiplied power consumption estimates by the baseline average and marginal emissions factors and then applied IEA's increase rate of 6.8%, per Table 5, based on IEA's "current policy" world CO2 emissions anticipated change by 2030.

The sustainable development scenario (SDS). This scenario considers the shift to cooler climates with low energy costs, friendlier regulations, and high-speed internet connectivity, e.g., certain regions of Scandinavia, Russia, Canada, and the United States, (Bendiksen, Gibbons, & Lim, 2018). This scenario's emissions factors were based on

IEA's "sustainable development" policy outlook that builds on the Sustainable Development Goals of the United Nations (IEA, 2017).

To estimate the amount of carbon emissions by 2028 under SDS, I multiplied power consumption estimates by the baseline average and marginal emissions factors and then applied IEA's decrease rate of 21.5%, per Table 5. This resulted in estimated carbon emissions decreases ranging between 94.4 to 225.4 MtCO2, with likely outlook at 155.2MtCO2. Based on IEA's "sustainable development" scenario, world's CO2 emissions are expected to decrease by 2030, if the integrated strategy for achieving policy objectives is respected worldwide. The policy aims "to provide an energy sector pathway that integrates three closely associated but distinct policy objectives: to ensure universal access to affordable, reliable and modern energy services by 2030; to substantially reduce the air pollution which causes deaths and illness; and to take effective action to combat climate change" (IEA, 2017).

This scenario considered a shift of mining pools locations to cooler, reliable, and more sustainable regions. International Energy Agency predicts that advanced economies and China energy demands will be met by low-carbon technologies and gas and therefore its carbon footprint is expected to shrink (IEA 2018). Based on the assumption that the current largest pools will be supported by low-carbon energies, evidenced by IEA's sustainable development scenario per Table 5 and that there will be a shift to cooler regions of Scandinavia, Russia, Canada and the United States, (Bendiksen, Gibbons, & Lim, 2018), I modified regional allocation of mining pools to 50% Asian (two-thirds in China), 25% European, and 25% North American. I then applied IEA's regional sustainable development emissions reductions rates to obtain carbon emissions results

under the sustainable development scenario. Lastly, to reflect on the limitations of the research and possible marginal error of estimates and assumption uses, I ran a sensitivity analysis, assuming 5% and 10% deviations.

The climate damages assessment. CO2 emissions were then converted into estimated climate damages using the US Federal Government's social cost of carbon (SCC) for projected 2028 emissions at $49/MTCO2, assuming a 3% discount rate (Figure 10). The social cost of carbon (SCC) is a present-valued dollar measure of the long-term damages caused per ton by carbon dioxide (CO2) emissions into the atmosphere (Goodkind et al., 2020). Rather than estimating monetary damages of producing cryptocurrency, I used a currently available peer reviewed study, which calculates human health, climate, and total damages of selected cryptocurrencies as a proxy. Goodkind et al.'s (2020) study introduces a comprehensive analysis of the per coin economic damages of air pollution emissions and associated human mortality and climate impacts of mining the four prominent cryptocurrencies (Bitcoin, Ethereum, Litecoin, and Monero) in the United States and China. Table 6 summarizes the results of the study, which concludes that in 2018, each $1 of Bitcoin value created was responsible for $0.49 in health and climate damages in the US and $0.37 in China (Goodkind et al., 2020).

Year	5% Average	**3% Average**	2.5% Average	High Impact (95th Pct at 3%)
2010	10	**31**	50	86
2011	11	**32**	51	90
2012	11	**33**	53	93
2013	11	**34**	54	97
2014	11	**35**	55	101
2015	11	**36**	56	105
2016	11	**38**	57	108
2017	11	**39**	59	112
2018	12	**40**	60	116
2019	12	**41**	61	120
2020	12	**42**	62	123
2021	12	**42**	63	126
2022	13	**43**	64	129
2023	13	**44**	65	132
2024	13	**45**	66	135
2025	14	**46**	68	138
2026	14	**47**	69	141
2027	15	**48**	70	143
2028	15	**49**	71	146
2029	15	**49**	72	149
2030	16	**50**	73	152

Figure 10. Annual social costs-CO2 Values: 2010-2050 (2007$/MtCo2) (US government, 2015).

Table 6. Mortality impacts, climate damages, and health damages of coin mining created by country, year, and cryptocurrency (Goodkind et al.'s, 2020).

		Mortality per million coins		Climate damages ($ per coin)		Health damages ($ per coin)		Damages (% of coin value)		Global coins mined (millions)
		USA	China	USA	China	USA[a]	China[b]	USA	China	
BTC	**2016**	4.6	9.6	74	86	53	11	21%	16%	1.0
	2017	19	40	311	359	222	45	19%	14%	0.70
	2018	115	239	1849	2135	1321	268	49%	37%	0.68
ETH	**2016**	0.03	0.06	0.49	0.57	0.35	0.07	9%	7%	10.8
	2017	0.59	1.2	9.5	11	6.8	1.4	8%	6%	8.7
	2018	2.5	5.2	40	46	29	5.8	21%	16%	6.6
LTC	**2016**	0.01	0.02	0.15	0.17	0.10	0.02	7%	5%	5.3
	2017	0.08	0.16	1.22	1.4	0.87	0.18	5%	4%	5.4
	2018	0.94	2.0	15.2	18	11	2.2	37%	28%	5.3
XMR	**2016**	0.02	0.05	0.35	0.41	0.25	0.05	27%	21%	3.1
	2017	0.19	0.39	3.0	3.5	2.2	0.44	8%	6%	1.9
	2018	1.0	2.1	17	19	12	2.4	22%	17%	1.1

Chapter III

Results

To address research questions and hypotheses, I first completed the cost benefit analysis and calculated the expected value of the cryptocurrencies (market capitalization) versus estimated electricity consumption costs associated with its production, comparing different scenarios of cryptocurrency evolution and energy development.

Cost Benefit Analysis

This study aimed to clarify cryptoasset value formation and quantify its economic benefit over a ten-year timeframe. Furthermore, this study assessed electricity consumption levels associated with the cryptocurrencies' mining and then quantified electricity consumption cost associated with cryptoasset value creation to derive a true profitability of the cryptocurrencies.

Cryptocurrencies' value assessment. Dowlat's (2018) study estimated the amount of cryptoasset market value needed to support economic activities will expand from projected $500B in 2019 to $3.6 trillion in 2028. However, per validation of the data used in the model, I identified that Dowlat's 2018 market cap value was 25% higher than 2018 actuals ($127 billion versus Dowlat's $170 billion input). Using 2018 actuals, I re-modeled the initial projections by applying 25% correction rate to the future values, resulting in an estimated $2.6 trillion of cryptoasset market value needed to support economic activities in 2028 (Figure11), based on +36% CAGR (Dowlat, 2018).

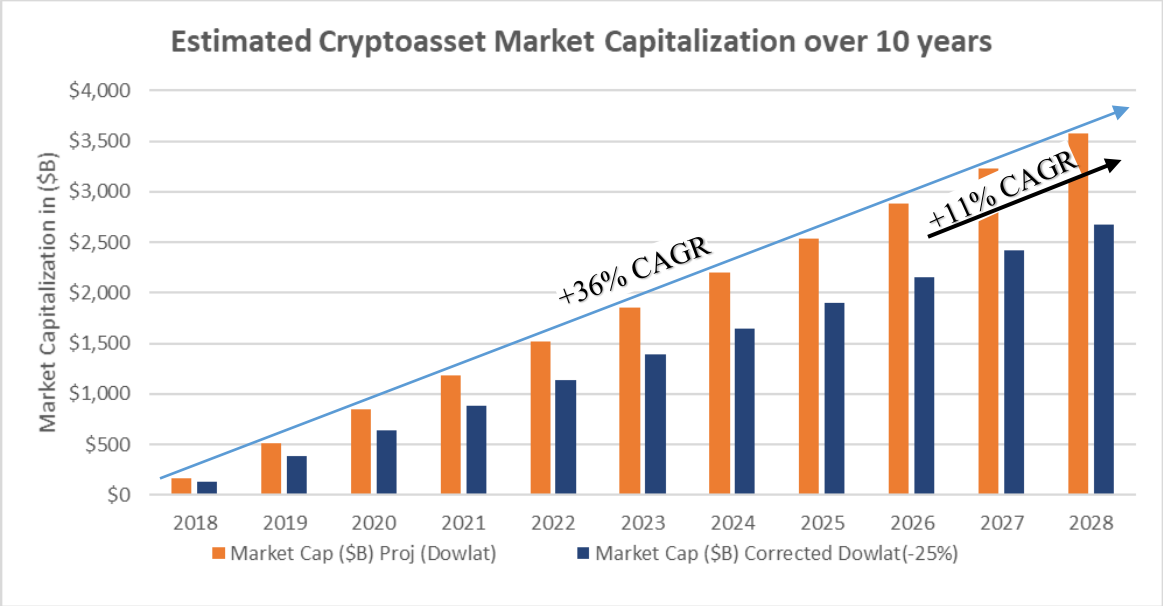


Figure 11. Estimated cryptocurrencies' market capitalization over 10 years (revised from Dowlat, 2018).

Dowlat's model projections were then compared to the cryptoasset forecast, based on collected five-year historical trend. The five-year historical data demonstrated unpredictable spikes with quarter over quarter market capitalization fluctuations ranging from negative 59% to 313% (Figure 12). Based on this growth pattern, a five-year market capitalization forecast was obtained through my modeling, resulting in forecasted market cap value of $600 billion by end of 2023, ranging from $200 billion lower bound to $1.1 trillion upper bound (Figure 13).

The forecast results in average 4% value deviation from Dowlat's corrected five year projections (Figure 14). Since the forecasting model was only based on the coin price multiplied by the number of coins to obtain the market capitalization value, and assumed that the underlying assets is moving +/- 25% (2018 actuals vs Dowlat's study input), the price alone was not compelling.

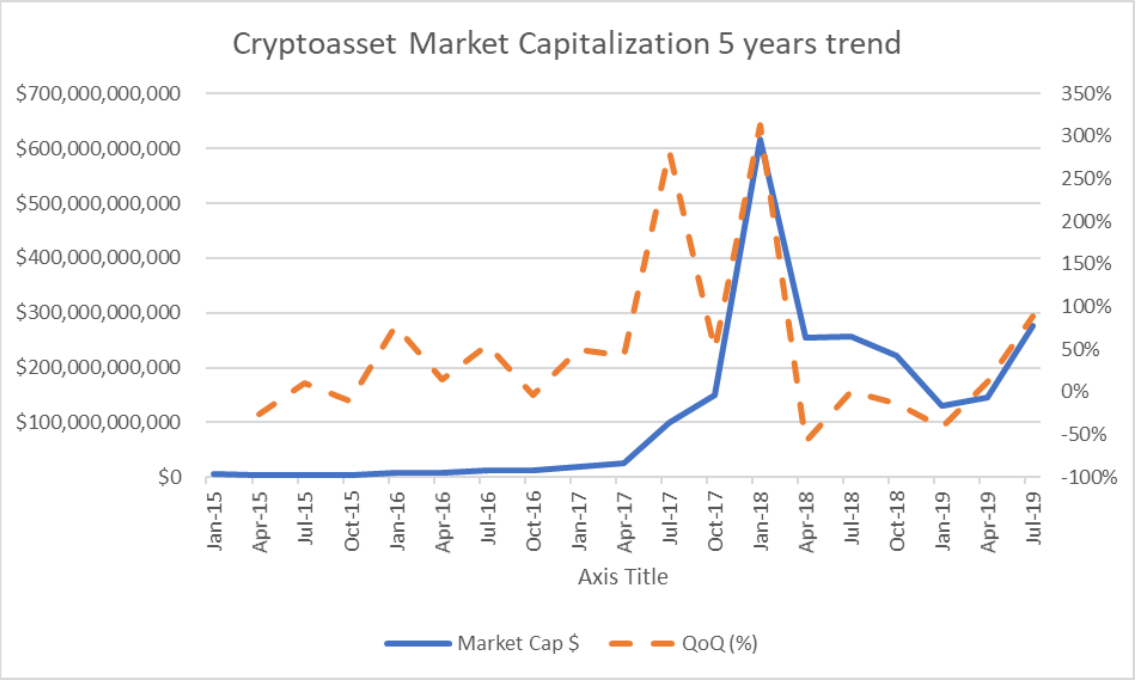


Figure 12. Cryptoasset market capitalization 2015-2018 (CoinMarketCap, 2019).

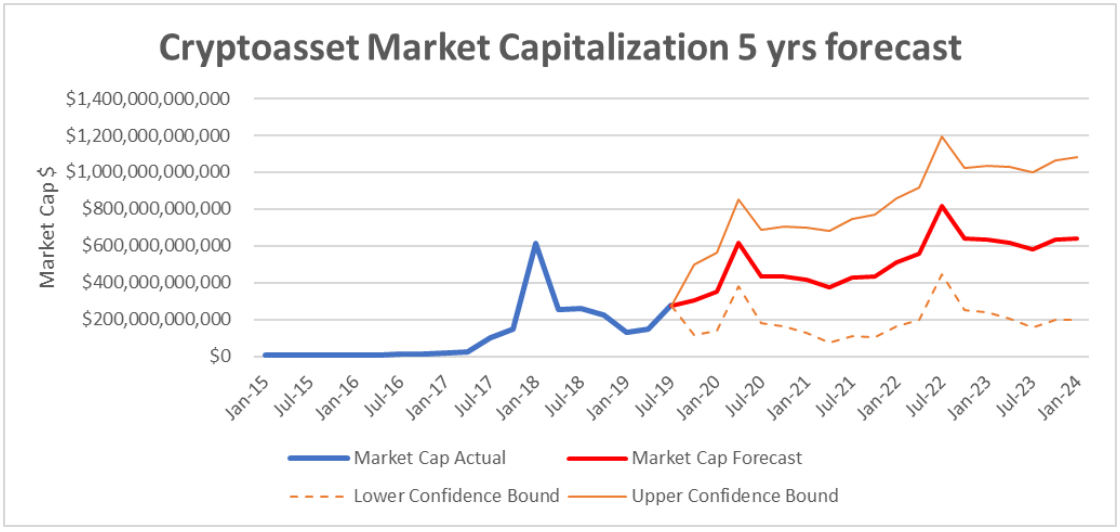


Figure 13. Cryptoasset market capitalization five- year forecast.

To aggregate future cash flow from cryptocurrencies' production over five years and obtain net present value (NPV), and to account for the risk of period over period

fluctuations, I assumed a 29.5% discount rate (based on 5 years CAGR). This resulted in NPV of $1.35 trillion compared to Dowlat's (2018) projected value of $1.39 trillion by 2023, a 2% difference. However, the NPV method is not straightforward to interpret because it depends on the interest rate chosen to measure the cash flow. To obtain the interest rate, I applied an annual rate of 29.5% over 5 years (PV=$381B, FV=$1.389B, n=5) per Dowlat's adjusted model.

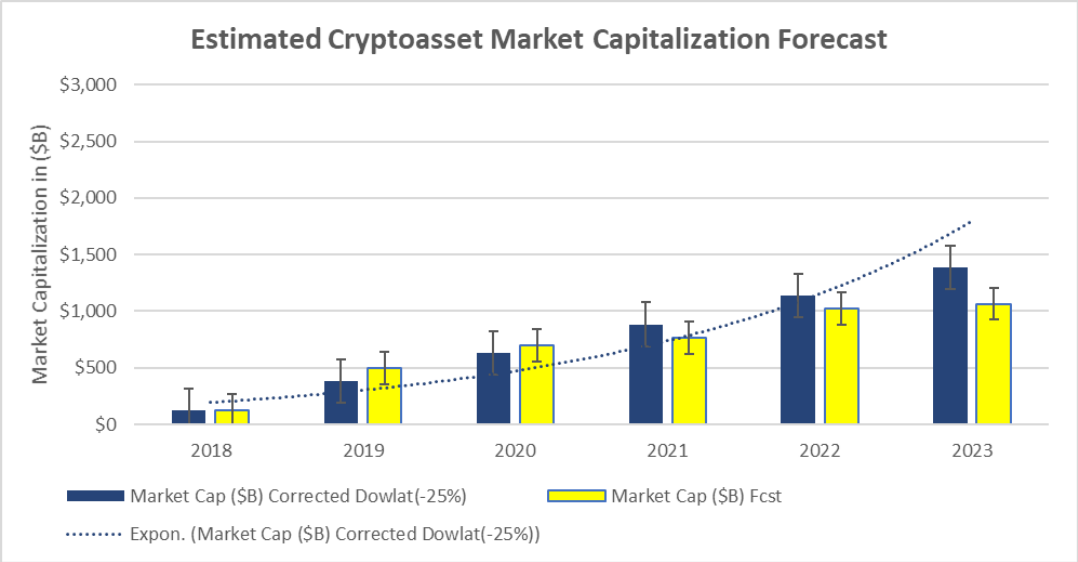


Figure 14. Estimated cryptocurrency market capitalization over 5 years.

Due to the identified 2% difference in estimates, sensitivity simulation examined a range of outcomes from varying cryptoasset growth rate (Table 3). Across the range of 5% changes in cryptoasset growth, cryptoasset market capitalization would range from a low of $2.4 trillion to a high of $2.9 trillion by 2028, assuming +36% CAGR. And the 2018 annual yield would be approximately $260 billion (ranging between $236 billion to $289 billion) (Table 7), assuming +11% CAGR per Figure 4 above.

Table 7. Sensitivity to cryptoasset growth (2028).

Cryptoasset Growth	-10%	-5%	0%	5%	10%
market cap 10-yrs yield ($T)	$ 2.41	$ 2.54	$ 2.68	$ 2.81	$ 2.95
market cap annual yield ($B)	$ 236	$ 250	$ 263	$ 276	$ 289

Cryptocurrencies' energy consumption projections. Results of the cryptocurrencies' electricity consumption projections were based on the historical trends and assumption of De Vries' (2018) study that cryptocurrencies' energy consumption is proportionate to its value creation. Figure 15 shows that the total cryptocurrencies' electricity consumption is characteristic of nonlinear growth, and the average increasing speed of electricity consumption in these years is about 13% per year, although there might be a slight short-term fluctuation.

Based on the regression analysis modeling, the electricity consumption needed to produce cryptocurrencies will likely reach 293TWh by 2028, with lower confidence bound at 196TWh and upper bound at 390TWh (Figure 7). In other words, the electricity consumption will increase by nearly $200 billion kWh relative to 2019 levels by the year of 2028. These estimates do not include the energy required for cooling systems or other maintenance aspects of running a mining operation, making this the minimum power requirement for each network (Krause & Tolaymat, 2018).

Based on this analysis, the estimated 2028 cryptocurrency electricity consumption level of 293 TWh (or even when considering upper bound forecast range) represents only 1% of 2018 United States electricity consumption (29,688 TWh) (EIA, 2019). Therefore, hypothesis 1a, that a ten-year period production of cryptocurrencies will require more electricity than used by the entire United States in 2018, was strongly rejected.

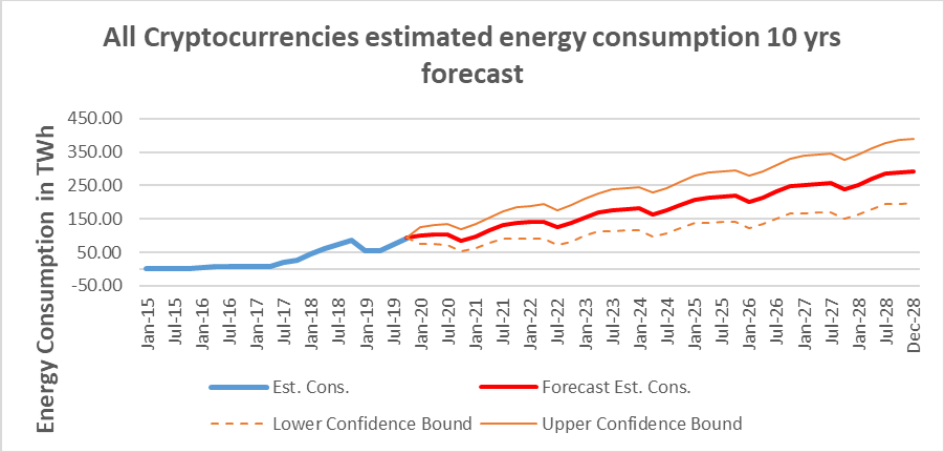


Figure 15. Cryptocurrencies estimated energy consumption ten-year forecast in TWh.

*Cryptocurrencies production cost assessmen*t. Based on the estimated energy consumption levels over a ten year period, I obtained cryptocurrencies' 2028 estimated likely electricity cost, considering EIA's energy outlook with projected 13.3 cents/kWh in the United States in ten-years. (EIA, 2019). Based on likely case of 293TWh electricity consumed by cryptocurrencies by 2028, the total likely electricity costs were estimated at $39 billion, with estimates ranging from $26 billion assuming the lower bound of 196TWh consumption, to $52 billion considering the upper bound at 390TWh consumption level.

A sensitivity analysis of +/-10% was performed to obtain electricity cost forecast range over a ten-year period, resulting in electricity cost ranging from $23.4 billion to $57.2 billion per Table 8, considering lower and upper bound projections.

Table 8. Sensitivity to cryptocurrency energy costs (in $ billion).

Cost estimates	-10%	-5%	0%	5%	10%
Likely Energy cost ($B)	35.1	37.1	39.0	41.0	42.9
Lower Bound Energy cost ($B)	23.4	24.7	26.0	27.3	28.6
Upper Bound Energy cost ($B)	46.8	49.4	52.0	54.6	57.2

Based on 2028 market capitalization annual yield estimates (ranging from $236 billion to $289 billion) and estimated energy consumption cost (ranging from $23.4 billion to $57.2 billion), it is evident that the hypothesis 1b of cryptocurrencies' 2028 value being less than the cost of the electricity required to generate it, is rejected. Based on the cryptocurrency growth trajectory, and assuming current policy energy source evolution, and the baseline scenario of mining facility locations, cryptocurrencies' ten year return on investment is positive.

Environmental Footprint Assessment

Assessment of the environmental footprint resulted in GHG emissions calculations using CO2 per kwh electricity parameters derived per assessment of a wide range of scenarios on energy consumption levels, major mining pool locations, and an energy source mix used in cryptocurrencies' production. Outputs of the CO2 emissions results were converted into climate damages.

The carbon emissions assessment. Cryptocurrencies' environmental impact derives from its massive energy consumption and use of specialized hardware. The assessment of the annual carbon emissions based on total electricity consumption estimates resulted in annual carbon emissions ranging between 21.5 to 53.6 MtCO2 per year, a ratio that sits between the levels produced by Bolivia and Portugal (Stoll, Klaaßen & Gallersdörfer, 2019). Translation of the cryptocurrencies' power consumption estimates into carbon emissions resulted in a very rough approximation of carbon emission ranging between 53 to 63.6 MtCO2, with the likely case at 58.3 MtCO2.

The carbon footprint ten-year outlook (2019-2028) resulted in a range of possible CO2 emissions and related health implications, based on the three scenarios I examined. The baseline scenario resulted in carbon emission estimates ranging between 120.4 to 287.5 MtCO2, with likely at 198 MtCO2. Calculations based on the current policy scenario (CPS) resulted in estimated carbon emission ranging between 142 to 339.1 MtCO2, with likely outlook at 233.5MtCO2 (Table 9). This is nearly on par with emissions caused by recent Australia's devastating bushfires (record 370 MtCO2 emitted from September 2019 to Jan 6, 2020), according to the European Union's ECMWF Copernicus Atmosphere Monitoring Service (Taylor, 2020).

The new policies scenario (NPS) resulted in estimated carbon emission ranging between 128.6 to 307.1 MtCO2, with likely outlook at 211.5MtCO2 (Table 9). The sustainable development scenario (SDS) simulation resulted in carbon emissions decreasing to a range between 40.5 to 80.5 MtCO2, with likely outlook at 60.5MtCO2.

The three scenarios sensitivity analysis (Table 9) illustrates lower and upper bound probable range of carbon footprint, assuming 5% and 10% deviations. Based on the geographical location of the major mining pools, further efficiencies can be obtained. The impact of emissions can be substantially reduced. However due to the lack of the precise data, this should be a focus of further research once data becomes available.

Table 9. Sensitivity to cryptocurrency carbon footprint (in MtCO2)

CO2 emissions sensitivity analysis (MtCO2)	-10%	-5%	0%	5%	10%
SDS -Likely	54.4	57.5	60.5	63.5	66.5
SDS- Lower Bound	36.4	38.4	40.5	42.5	44.5
SDS- Upper Bound	72.5	76.5	80.5	84.5	88.6
CPS- Likely	210.2	221.9	233.5	245.2	256.9
CPS- Lower Bound	127.8	134.9	142.0	149.1	156.2
CPS- Upper Bound	305.2	322.2	339.1	356.1	373.1
NPS -Likely	190.4	200.9	211.5	222.1	232.7
NPS- Lower Bound	115.7	122.2	128.6	135.0	141.5
NPS- Upper Bound	276.4	291.8	307.1	322.5	337.9

The climate damages assessment. Table 10 summarizes upper and lower bound range of climate damages in a ten-year period across the three scenarios, with likely scenario under the current policy (CPS) estimated at $11.4 billion of annual climate damages, with possible range between $7.0 billion to $16.6 billion for lower and upper bound, respectively (Table 10).

Table 10. Sensitivity to cryptocurrency annual climate damages-SCC (in $ billion).

Annual Climate Damages -SCC (2007$B/MtCO2)	-10%	-5%	0%	5%	10%
SDS -Likely	$ 2.7	$ 2.8	$ 3.0	$ 3.1	$ 3.3
SDS- Lower Bound	$ 1.8	$ 1.9	$ 2.0	$ 2.1	$ 2.2
SDS- Upper Bound	$ 3.6	$ 3.7	$ 3.9	$ 4.1	$ 4.3
CPS- Likely	$ 10.3	$ 10.9	$ 11.4	$ 12.0	$ 12.6
CPS- Lower Bound	$ 6.3	$ 6.6	$ 7.0	$ 7.3	$ 7.7
CPS- Upper Bound	$ 15.0	$ 15.8	$ 16.6	$ 17.4	$ 18.3
NPS -Likely	$ 9.3	$ 9.8	$ 10.4	$ 10.9	$ 11.4
NPS- Lower Bound	$ 5.7	$ 6.0	$ 6.3	$ 6.6	$ 6.9
NPS- Upper Bound	$ 13.5	$ 14.3	$ 15.1	$ 15.8	$ 16.6

Based on 2018 benchmark of Goodkind et al.'s study (2020) that each $1 of Bitcoin value created was responsible for $0.49 in health and climate damages in the US, I estimated that total cryptocurrency industry can trigger approximately $0.66 in health and climate damages for each cryptocoin value created, based on the US results as a proxy. This result is also based on a previous assumption that Bitcoin represents approximately 73.9% of total cryptocurrency market capitalization (as of August 2019) and its energy consumption is correlated to value creation per De Vries' (2018) study.

In summary, based on IEA's emissions outlook and assuming the previously calculated 275% increase in energy consumption from cryptocurrencies over 10 year-period, cryptocurrencies estimated annual CO2 emissions level will increase by 301% to approximately 233.5MtCO2 (likely scenario based on current policies). Annual CO2

emissions will trigger roughly $11.4 billion of climate damages with $1 of cryptocoin value created being responsible for $0.66 in health and climate damages in the United States.

It is evident that rapid growth in cryptocurrencies and associated energy consumption will lead to a significant increase in greenhouse gas emissions levels and other air pollutants in the atmosphere, but its overall impact will potentially be offset by the role of the renewable energy in cryptocurrency development. Under the sustainable development scenario, if sustainable policies are globally adopted, emissions will increase by 167% to approximately 155.2MtCO2 with the lower range estimated at 94.4 MtCO2 and subsequently lower health implications,

If the cryptocurrency industry's projected carbon footprint and associated health implications by 2028 are compared with the United States CO2 emissions levels in 2018, estimated at 5,269 MMtCO2 per EIA's (2019) report, it is evident that the second hypothesis is rejected. However, under the current policy scenario, cryptocurrencies' annual carbon footprint by 2028 will account for approximately 1% of 2018 world's overall CO2 emissions. Climate damage is estimated at $0.66 per each $1 of cryptocoin value. This is non-negligible fraction of the world's emissions and the resulting global health impact. Due to such high social costs, cryptocurrencies' price must continue rising faster than the social costs in order to maintain positive net benefits for society (Goodkind et al., 2020).

Chapter IV

Discussion

This research examined the challenges associated with cryptocurrencies' projected growth, its scalability, and the sustainability of the model, which compares its environmental impact to the benefits of this volatile financial system.

Research Limitations and Caveats

Limitations for this research include potential problems with securing the most accurate data sets for cryptocurrency valuation and projected energy source modeling scenarios. The model was generalizable to the entire cryptocurrency industry, but the conditions might restrict this research to the in-depth analysis of a limited number of cryptocurrencies where reliable data can be secured. In this study, I used different valuation models for predictions of market capitalization and energy consumption. A limited number of samples and historical data were used to construct a predictive model with relatively high prediction accuracy. The results of the data analysis are vulnerable to the uncertainties of future. Therefore, data projections only provide likely results based on the assumptions applied in the framework, and these results vary when compared to the scenarios analyzed in the research.

My valuation framework variables depend on the assumptions the research operated under, and therefore the model inputs were limited by the accuracy of those assumptions. The research estimated that the top three cryptocurrencies represented 86.4% of total cryptocurrency market cap and power demand as of August 31st, 2019.

This projection was made with a level of uncertainty due to the seasonal fluctuations. Therefore, estimates for the top three cryptocurrencies in proportion to the total crypto industry could be too high, in which case the total cryptocurrency energy consumption estimate would be lower than the actual demand, and thus future environmental impacts for any of the cryptocurrencies may be greater or less than those determined in current assessment (CBECI, 2019).

The analysis of the global energy source projections allowed me to separate the most important variables to determine the range of energy source scenarios. Lack of transparency and traceability behind the mining locations also caused assessment limitations. Therefore, model results might vary significantly depending on the selected locations and related energy sources available in those locations. The environmental footprint assessment was limited to the calculation of the carbon dioxide emissions, the climate damages and possible health impacts that resulted. Accordingly, I did not provide a full spectrum of the environmental implications; however, I based the calculation on most recent peer reviewed studies. Increased greenhouse gas levels, such as CO2, have direct impact on health with increased risk of morbidity and mortality due to reduced air quality, which causes health issues such as ischemic heart disease, stroke, and lung cancer (Bublitz et al., 2019).

Analysis of Crypto Mining Protocol Alternatives

One option for reducing cryptocurrency energy consumption involves transitioning from “Proof-of-Work” (PoW) to alternative protocols (consensus algorithm) to validate transfers. Many alternatives exist that are conceptually less energy intensive than PoW, and these alternatives are accompanied by multiple advantages as well as

some limitations. Recent CRS (2019) report examines algorithmic alternatives and defines two algorithms that require less energy than PoW: "Proof-of-Stake" (PoS) and "Proof-of-Authority" (PoA), which are compared below and illustrated in Figure 16

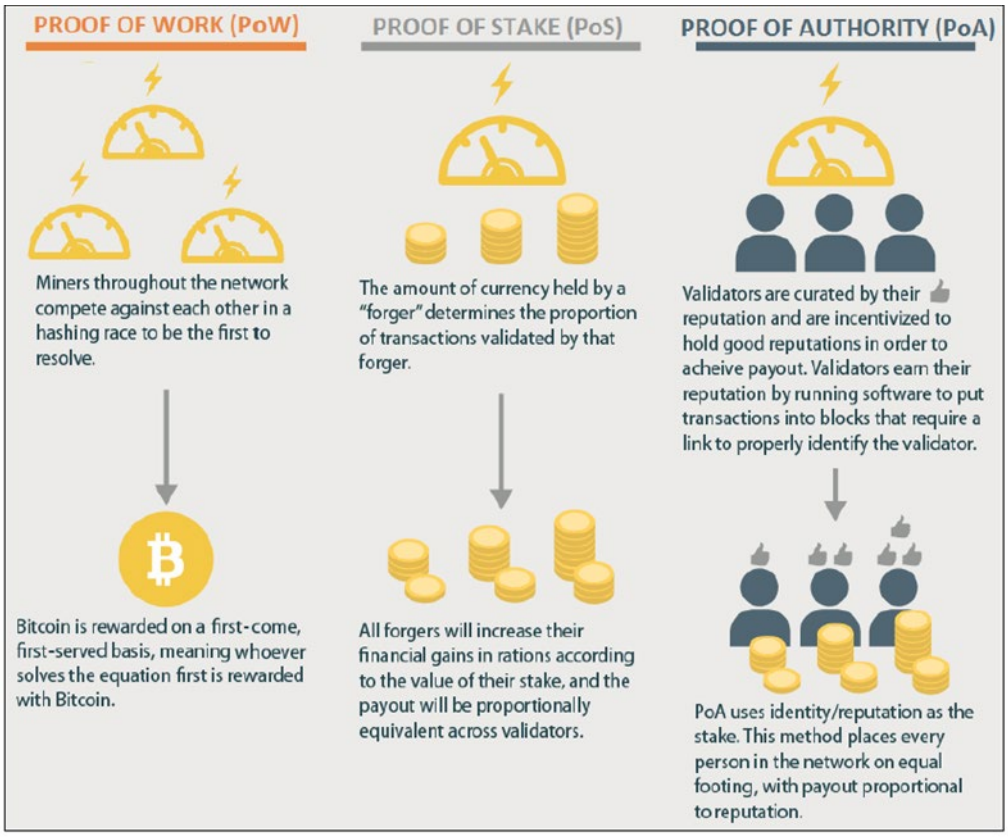


Figure 16. Algorithmic approaches to cryptomining: 3 approaches compared (CRS, 2019).

(CRS, 2019). Each algorithm presents tradeoffs; for example, some algorithmic attributes facilitate scalability and others facilitate speed of transactions (CRS, 2019).

Energy policy analysts state that PoS skips the energy intense hashing race of PoW as "All of the currency is already created, and the amount is stagnant. Forgers earn currency through transaction fees for building a new block (and thereby validating a transaction)" (CRS, 2019). Potential energy reductions from use of PoS are leading to changes in some

major cryptocurrencies, like the Ethereum platform plans to move to a PoS system and is currently working on the remaining challenges, such as maintaining a decentralized system (CRS, 2019). On the other hand, PoA provides a level of scalability and security within private networks that PoS or PoW cannot (CRS, 2019). While PoS and PoA both reduce energy consumption levels and require far less sophisticated equipment, they both have limitations as they create a more controlling and limited environment (CRS, 2019). Accurate assessment of the advantages and disadvantages of cryptocurrency technology and preferred algorithm mechanisms could have immense economic and environmental impact and should be a future focus.

Conclusions

This research investigated the correlation between cryptocurrencies' electricity consumption growth and the projected changes to the global energy sources available for its production and data storage. Prediction of electricity consumption for cryptocurrency plays an important role in cryptocurrency development and economic advancement and is also important for policy makers (Li & Zhang, 2018). Accurate prediction results could facilitate effective implementation of electricity supply policies and determine what preferred algorithm mechanisms are used. In addition, the potential application of blockchain technology to the energy sector (and other sectors) will depend upon the ability for these technologies to provide transparent, secure, scalable, and timely transaction validation (CRS, 2019). Although this research was scenario based, the model was generalizable to different cryptocurrencies with similar parameters and was used to determine cryptocurrency's value and associated environmental footprint based on the manipulation of the different parameters.

This research compares cryptocurrencies' ten-year energy consumption projections and associated energy cost against cryptocurrencies' market capitalization value based on predicted growth trends and energy sector development scenarios. Results showed that by 2028, the amount of cryptocurrency market value needed to support economic activities would expand from current $240 billion to a range between $2.4 trillion to $2.9 trillion, assuming +36% CAGR and 2018 annual yield was estimated at around $260 billion, ranging between $236 billion to $289 billion. The rising electricity requirements to produce cryptocurrency could lead to energy consumption ranging between 196TWh to 390TWh, with likely case illustrated at 293TWh, equivalent to 1 % of US electricity consumed in 2018 (EIA, 2019). This energy consumption level would generate energy costs ranging between $23 to $57 billion per year when considering lower and upper bound projections. Furthermore, the research explored the consequences of cryptocurrencies' environmental footprint based on the projected changes to the energy supply mix over a ten-year period. Results indicate that projected energy consumption levels would generate carbon emissions ranging between 53 to 63.6 MtCO2.

Cryptocurrencies' exponential growth trajectory, paired with its high energy dependent production systems, might lead to economic and environmental threats unless a sustainable development scenario with the integrated strategy for achieving policy objectives is adopted worldwide. According to International Energy Agency's energy projections, by 2040 the global energy supply mix will fluctuate from fossil fuels' current dominance towards renewable energy (IEA, 2018). Therefore, projected changes to the global energy sources available for cryptocurrency production and its environmental

footprint were assessed. Crypto "mining" factories' locations would play a key role in cryptocurrencies' future value assessment, as its energy cost and environmental footprint directly correlates with energy sources available in different parts of the world.

Research results indicate that with increased penetration of renewable energy into the electricity supply mix used by mining, as well as the shift from current policy to sustainable development policy, emissions will decrease, ranging from 48 to 114MtCO2, considering lower and upper bound projections. A further shift in the geographic distribution of the major mining pools will occur from the current estimate at 68% Asian, 17% European, and 15% North American to a sustainable development scenario with 50% Asian (two-thirds in China), 25% European, and 25% North American; this would have a material impact on the cost of cryptocurrency operations and its environmental footprint (Stoll, Klaaßen & Gallersdörfer, 2019). Results indicated that such shift would decrease emissions by additional 54 to 145MtCO2.

Under a likely scenario based on current policies, annual CO2 emissions would trigger roughly $11.4 billion of climate damages, while switching to the sustainable development scenario would lead to a reduction of annual climate damages to $2.7 billion. Furthermore, results illustrate a scenario that assumed for each $1 of cryptocurrency coin value created, $0.66 in health and climate damages would be created.

One option to reduce cryptocurrency energy consumption is to choose the right technology to support cryptocurrency industry growth and shift away from energy-hungry consensus algorithms. I compared alternative crypto mining protocols that could be used in cryptocurrencies' production with minimal environmental footprint and

suggested that shift away from PoW to PoS or PoA could be beneficiary, as they both reduce energy consumption levels and require far less sophisticated equipment.

Under current policy, cryptocurrencies annual carbon footprint by 2028 would account for approximately 1% of 2018 world's overall CO2 emissions and associated high social costs. To maintain positive net benefit for the society, the crypto industry needs to ensure cryptocurrency price continue rising, faster than energy and social costs attached to its development. The research results do not suggest that cryptocurrency is "burning down the planet," but the negative externalities identified in the research should be considered. Unlocking blockchain technology potential for the energy sector could be highly disruptive, considering interesting application in net metering and a transactional grid, smart contracts, distributed energy resource record keeping, and ownership records, to name a few (CRS, 2019). This research results suggest that externalities should be considered by policymakers in order to establish the appropriate guidelines in embracing blockchain adoption and cryptocurrency's energy intense processes.

A future focus of this work should include an accurate assessment of the advantages and disadvantages of cryptocurrency technology and preferred algorithm mechanisms, which could have an immense economic and environmental impact. Further understanding of the externalities associated with cryptocurrency should act as a catalyst for additional research. As more data becomes available on geographical distribution of the major mining pools and energy mix used in those locations, this could be applied in further research on the climate damage and health implications resulting from cryptocurrency mining. This research assessment into the true profitability of cryptocurrency and its net benefit to society might help evolve this field.

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