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Cryptodamages: Monetary value estimates of the air pollution and human health impacts of cryptocurrency mining

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ABSTRACT

Cryptocurrency mining uses significant amounts of energy as part of the proof-of-work time-stamping scheme to add new blocks to the chain. Expanding upon previously calculated energy use patterns for mining four prominent cryptocurrencies (Bitcoin, Ethereum, Litecoin, and Monero), we estimate the per coin economic damages of air pollution emissions and associated human mortality and climate impacts of mining these cryptocurrencies in the US and China. Results indicate 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. The similar value in China relative to the US occurs despite the extremely large disparity between the value of a statistical life estimate for the US relative to that of China. Further, with each cryptocurrency, the rising electricity requirements to produce a single coin can lead to an almost inevitable cliff of negative net social benefits, absent perpetual price increases. For example, in December 2018, our results illustrate a case (for Bitcoin) where the health and climate change "cryptodamages" roughly match each $1 of coin value created. We close with discussion of policy implications.

1. Introduction and background

As an anonymized and decentralized production process, digital currencies using cryptographic blockchain verification for securing transactions are seen as a transformative technology that circumvents traditional banking and governmental regulatory mechanisms of more centralized fiat currencies ([1]; and see review in [2]). For proponents, cryptocurrencies generate important social benefits for securely transferring money and information, as well as serving as potential stores of wealth. The libertarian, anti-establishment appeal is represented in the independent production process ("mining"), which is independent of any government, regulatory entity, or particular geographic locality. Originally, all that was necessary to mine was access to electricity (the cheaper the better), computer hardware (with some spare CPU cycles), an internet/network connection (the faster the better), and a heavy dose of entrepreneurial spirit [1]. But, for many prominent cryptocurrencies, opportunities for profitable mining currently appear to require highly dedicated or specialized hardware concentrated in large-scale mining farms or pools [1,3,4,5,6].

Beginning with Bitcoin in 2009 (attributed to the elusive Nakamoto [7]), there are now more than 2500 cryptocurrencies, which generally share a reliance on the blockchain technology. In brief, blockchain is commonly referred to as a *decentralized, public ledger* that uniquely identifies all transactions using any particular cryptocurrency; the blockchain contains the blocks of digital information that record batches of transactions (with dates, times, amounts, participants [with unique digital signatures, rather than names or identifying information] and a unique transaction identifier or hash),[1] in a distributed peer-to-peer network of computers. Independent individuals or groups of miners compete using brute force computing power to be the first to solve complex algorithms and provide the hash identifier for a block, and if successful, then are rewarded with units of the cryptocurrency. Data from new, verified transactions are then added to the blockchain. While alternatives exist, cryptocurrency applications using blockchain remain dominated by the proof-of-work (POW) process used in the original Bitcoin, where the probability of successful mining is increased by the amount of computing work expended.

Thus, mining generates financial value, but consumes electricity in

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[1] A hash function, as commonly used in cryptography, generally refers to using mathematical algorithms to map or convert some arbitrarily long string of numbers and letters into some unique output (or hash) of fixed size.

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doing so. The complication is that the supply of any cryptocurrency coin is typically finite and made available according to prescribed rules that asymptotically approach some fixed amount at a specified point in time. Specifically, as the supply of new coins slows, the implication of a POW process is that the competing computing effort to mine coins must necessarily increase, thus requiring ever increasing amounts of electricity. This process amounts to sequential rounds of a winner-take-all tournament (akin theoretically to R&D tournaments [8]), where the costs associated with winning each round progressively increase. Thus, the "strange math" [6] of cryptocurrency provision based on a POW process generates intense electricity resource use [5,8,9], potentially creating negative—and growing—environmental and health costs that may be high and are not borne by the miners [10]. Our focus here is on beginning to monetize these electricity-related social costs.

As with any emergent technology, there needs to be careful consideration of its environmental and health impacts on society. In the emerging literature considering these impacts, Krause and Tolaymat [1] push such assessments significantly forward by quantifying the energy and carbon emissions for mining four prominent cryptocurrencies (Bitcoin (BTC), Ethereum (ETH), Litecoin (LTE), and Monero (XMR), all identified as using a POW process). They pursue the following questions: (i) do these cryptocurrencies require a similar energy supply to function?; (ii) what conventional processes or services would "cryptomining" compare to (e.g., gold mining), in terms of energy invested and value extracted?; and (iii) what carbon impacts might this energy consumption generate? They find that cryptomining of BTC, ETH, LTC, and XMR tends to consume more energy than traditional mineral mining such as copper, gold, platinum metals, and rare earth metals (with the exception of aluminum, which has high electricity consumption) in producing an equivalent market value. Their results additionally indicate that energy consumption requirements are generally expected to increase, for reasons previously discussed, and that BTC consumed more electricity than Ireland (26 TWh yr^{-1}) or Hong Kong (44 TWh yr^{-1}) in 2017. Finally, for the 2.5-year period (January 1, 2016 to June 30, 2018), they estimate that the four prominent cryptocurrencies were responsible for 3 – 15 million tonnes (t) of CO_2 emissions. More recently, Stoll et al. [11], using IP-addresses to attempt to locate mining, estimate substantially larger CO_2 emissions associated with BTC, in excess of 20 million t per year.

In this research, we extend the discussion in Krause and Tolaymat [1] to ask the next logical question: "What are the economic damages connected to air pollution, health and climate impacts of mining cryptocurrencies?" Taking the Krause and Tolaymat [1] results for the US and China, we use commonly available simulation models, exposure-response functions, and available estimates of the social costs of carbon, and value of statistical life (VSL) measures to monetize the negative environmental externalities of air pollution and human health damages. We focus on the health and climate damages associated with mining four coins over the period 2016 – 2018; the same four coins considered in Krause and Tolaymat [1]. These four coins—BTC, ETH, LTC and XMR—accounted for 57.2 percent of the $369 billion in total market capitalization for 1658 listed cryptocurrencies as of March 15, 2018; BTC alone accounted for 37.8% [12].[2]

The electricity consumption of mining cryptocurrencies is large and growing rapidly. For example, in January of 2016, each BTC mined required 1005 kWh of electricity; but by June 2018, each coin mined required 60,461 kWh [1]. In 2016 there were ~1 million BTC mined, which consumed 2.5 billion kWh of electricity; in 2018 the total number of coins mined dropped to 700,000, but electricity consumption increased to 47.9 billion kWh. This usage creates negative social externalities, most significantly by contributing to climate change and impacting human health from the burning of fossil fuels. It was recently argued that CO_2 emissions from Bitcoin mining alone could push global warming above the 2 °C threshold of concern [13]. Economists use a battery of techniques to estimate the monetary damages connected to these non-market negative externalities, which by definition are not accounted for in the market production or consumption of a good or service (see [14]). In this case, the health and climate impacts of cryptocurrency mining, which we refer to here as "cryptodamages."

Rather than attempt a global damage estimate from overall production of cryptocurrencies under the broadest of assumptions for what are extremely dynamic and volatile markets, we make an initial attempt at a more refined approach, using four prominent POW-process based coins and two countries. Specifically, given available information constraints, we examine these externalities on a *per-coin generated basis*, where we have more detailed information about the spatial and temporal characteristics of the required electricity generation. Spatially, emission rates for CO_2 and regional air pollutants from electricity generation vary substantially, based on the fuels used and the generation methods. Human health effects from regional air pollutants also have large spatial variability depending on the proximity of populations to emission sources. Thus, to account for the spatial variability of coin generation, we calculate externalities on a per-coin-basis for electricity generation in the US and China, which are two dominant players in the cryptocurrency network, and which have very different electricity production and air pollution emission profiles.[3]

2. Methods

We start by collecting data on emission rates per kWh of electricity generation by country (US and China) for four pollutants commonly created by burning fossil fuels to produce energy: carbon dioxide (CO_2), fine particulate matter ($PM_{2.5}$), nitrogen oxides (NO_x) and sulfur dioxide (SO_2) [16,17,18].[4] Next, we combine these emission rates with the kWh of electricity usage per coin created [1].[5] Together, this provides the average emissions released (from all energy sources; fossil fuels and renewables) to generate one coin. CO_2 emissions are used to calculate the climate damages per coin created. Exposure to pollution associated with the other three pollutants ($PM_{2.5}$, NO_x and SO_2) increases the risk of premature mortality [20,21]. Hence, we use these emissions to calculate the mortality impact of creating one coin in each country, and the monetary damages of the premature deaths.[6]

Electricity requirements to produce one coin for each day are derived from the network hashrate of the blockchain, a publicly available figure [1,22]. The hashrate is a measuring unit, which identifies the amount of power consumed by all the operations in a cryptocurrency

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[2] For perspective, as of approximately one year later (March 2, 2019), total market capitalization had fallen to $130.7 billion, but the number of listed cryptocurrencies has grown to 2526, with BTC, ETH, LTC and XMR accounting for 65.8 percent of total market capitalization; BTC alone accounted for 50.4 percent (for current estimates see Investing.com at: https://www.investing.com/crypto/currencies).

[3] For context, as of June 2018, over 80% of Bitcoin mining was performed by six mining pools, and five of those six pools are managed (but not necessarily physically located) in China [15]. In the US, cryptocurrency mining is a significant source of controversy, partially related to its offsetting effects on fossil fuel use and associated climate change impacts (e.g., [6]).

[4] There are several other fossil fuel power plant pollutants that are not considered here, but which may affect human health, including mercury, cadmium, chromium, and nickel. Data limitations preclude their inclusion here. Thus, our estimates are likely a lower bound on actual damages.

[5] The data in Krause and Tolaymat [1] stop at June 30, 2018, so we collected original data on electricity usage and coins generated to extend the dataset from July 1, 2018 to December 31, 2018. These extended data are available from https://bitinfocharts.com/ [19] for the network hashrate, block time, and coin price.

[6] There are other externalities associated with these emissions that are not included in our damages estimates. For instance, SO_2 emissions contributes to acid rain and NO_x emissions contribute to ground-level ozone.

network to mine blocks and receive the currency reward. Stated simply, "hashrates are the number of calculations (hash functions) performed on the network in seconds" ([1], p. 711). Hashrates increase with the intensity of the computational competition.

The great unanswered question faced when exploring cryptodamages is that while we can identify select geographic hotspots of production we currently do not know in the aggregate where the electricity used in cryptocurrency mining is physically produced. This is because we, like Krause and Tolaymat [1], do not know the physical locations of cryptocurrency miners, whether individuals, groups or aggregates in, say, a region or country. There is considerable evidence of concentration of mining operations in particular locations, typically where reliable electricity is cheaply available, though, precise data are lacking (e.g., [6,15]). In the US, perhaps the most well-known concentration is the Mid-Columbia Basin area in central and eastern Washington State, where cheap electricity is produced by hydropower along the Columbia River [4,6], however, mining in other US locations also occurs (see [11] and news references in [23,24], and [25]). There is also evidence of large mining camps in China [15]. With time and emergent research (e.g., see [11]) there may be improved information about the amounts of electricity devoted to mining cryptocurrencies for particular locations or regions, but it is currently not available.

Therefore, we aim to characterize the externalities associated with the production of a single coin in both the US and China, where emissions rates per kWh will differ substantially given underlying differences in how power is produced—i.e., China relies extensively on coal power (> 60% of electricity generation) while the US is more balanced (32% natural gas, 30% coal, 20% nuclear, etc.). Emission rates of CO_2 per kWh of electricity produced in 2016 were obtained[7] [17,18] and combined with electricity usage per coin to produce CO_2 emissions per coin created. Then, we convert CO_2 emissions into estimated climate damages using the US Federal Government's social cost of carbon (SCC) for 2020 emissions and assuming a 3% discount rate [26]. The SCC is estimated at \$51 t^{-1} in 2018 US Dollars.[8]

Estimating mortality impacts of emissions from cryptocurrency generation is more complicated. The general steps to convert emissions into mortality impacts, and ultimately into monetary damages are as follows: (i) data from emission rates from electricity generation are collected; (ii) human exposures to the pollutants are estimated; (iii) exposure is converted into mortality impacts using exposure-response functions, and; (iv) premature mortality is converted into monetary damages using the value of a statistical life (VSL). For (i), we collect data for the US [16,17] and China [18]. For the US, these data are emissions of $PM_{2.5}$, NO_x, and SO_2 and electricity generation for every electricity generating unit (EGU) in the country. For China, we collect aggregate data of emissions of these pollutants from the electricity generation sector divided by the net electricity generation [29]. For both countries, we did not want to exclude non-emitting electricity generation, rather we want the emission profile of a unit of electricity from all sources in each country. The choice of pollutant species is based on their high rates of emissions from electricity generation, and their known impact to premature mortality. Exposure to $PM_{2.5}$ is associated with an increased risk of adult-premature mortality [20,21]. $PM_{2.5}$ air pollution consists of primary $PM_{2.5}$ and secondary species: SO_2 and NO_x are $PM_{2.5}$ precursor emissions that form into secondary $PM_{2.5}$ in the atmosphere. We estimate the mortality impacts of SO_2 and NO_x from their contributions to $PM_{2.5}$ concentrations.

Calculating human exposure to $PM_{2.5}$ from electricity emissions (step (ii) above) is complicated and the data are not readily available for China. We do, however, have detailed estimates of these relationships for US emissions. We use this US data to estimate the relationship for China, which we explain in detail below. First, we describe the relationship between electricity emissions and exposures in the US. Transport of emissions of each pollutant from every EGU in the contiguous US is modeled using the Intervention Model for Air Pollution (InMAP) [30,31]. InMAP estimates the change in $PM_{2.5}$ concentrations from a unit of emissions. Changes in $PM_{2.5}$ concentrations are translated into changes in the risk of premature mortality using a commonly adopted concentration-response function [20]. Combining these results with emissions per unit of electricity for the three pollutants, we estimate the mortality impact per kWh of electricity generation at each EGU. The sum of the impact for the three pollutants is the total mortality impact per kWh of electricity generated at every EGU in the US. We then allocate the emission profile of electricity at EGUs to locations (or grid cells in the model) where people consume electricity.[9] The emission profile in a grid cell is based on a weighted average of all EGUs within 250 km of the cell centroid, weighted by the inverse distance to the EGU and the quantity of electricity generated (see Fig. 1). Combining the health damages with climate damages per kWh, we estimate that one-third of electricity in the US is produced with less than 1 cent kWh^{-1} of damages, and one-tenth of electricity is produced with greater than 10 cents kWh^{-1} of damages.

We use the mortality impact per unit of emissions in the US to estimate the mortality impacts in China. Crucially, the impact of emissions is strongly related to the size of the population in the area surrounding the emission source [32,33]. We relate the population density in a 50 km radius around each emission source in the US with the mortality impact of those emissions (see Fig. 2). We apply these relationships to China based on its unique population density to estimate the average mortality impact per unit of emissions. While we know the population density of both countries, this is not the appropriate value to apply to the estimated functions. The population density around EGU emission sources in the US is substantially greater, on average, than the population density of the country as a whole. For example, the population density around EGU SO_2 emissions is 88 persons km^{-2}, compared with 37 persons km^{-2} for the contiguous US. We use the ratio of each pollutant to population density to the contiguous US population density to adjust the population density of emission sources in China. The SO_2 population density ratio is 2.9, which when applied to China, with an overall population density of 145 persons km^{-2}, yields an estimated "SO_2" population density for China of 346 persons km^{-2}. We apply this population-density value to the mortality-impact relationship (best-fit lines in Fig. 2). This process produces an estimate of the mortality per tonne of emissions for each pollutant from electricity generation in China. Our estimate of the ratio of mortality impacts per unit of

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[7] US electricity emissions are in CO_2 equivalents (CO_2e), which includes methane and nitrous oxide. CO_2 emissions constitute 99.4% of CO_2e for US electricity generation.

[8] The social cost of carbon (SCC) is a present-valued dollar measure of the long-term damages caused per t by carbon dioxide (CO_2) emissions into the atmosphere. A topic of considerable policy debate, SCC estimates are used by the US EPA and other US government bodies in cost-benefit analyses of regulatory actions (e.g., for climate change impacts) [27]. For this analysis, we use the most recent US Interagency Working Group (2016) SCC estimate produced during the Obama Administration, and converted into 2018 values. The Interagency Working Group also produced estimates using higher (5%) and lower (2.5%) discount rates which substantially impact the magnitude of the SCC. It should be noted that in 2017 the Trump Administration altered the methodology used in calculating SCC to produce estimates in the \$1 to \$6 range t^{-1} of CO_2 emissions, which is drastically lower than estimates used here. However, other sources have recently argued that SCC estimates should be significantly higher than those used here (e.g., see [27]), due to significantly underestimating the effects on agriculture [28].

[9] The InMAP model has variably-sized grid cells based on population density. The grid cells range from 48 km^2 in rural areas to 1 km^2 in dense urban areas.

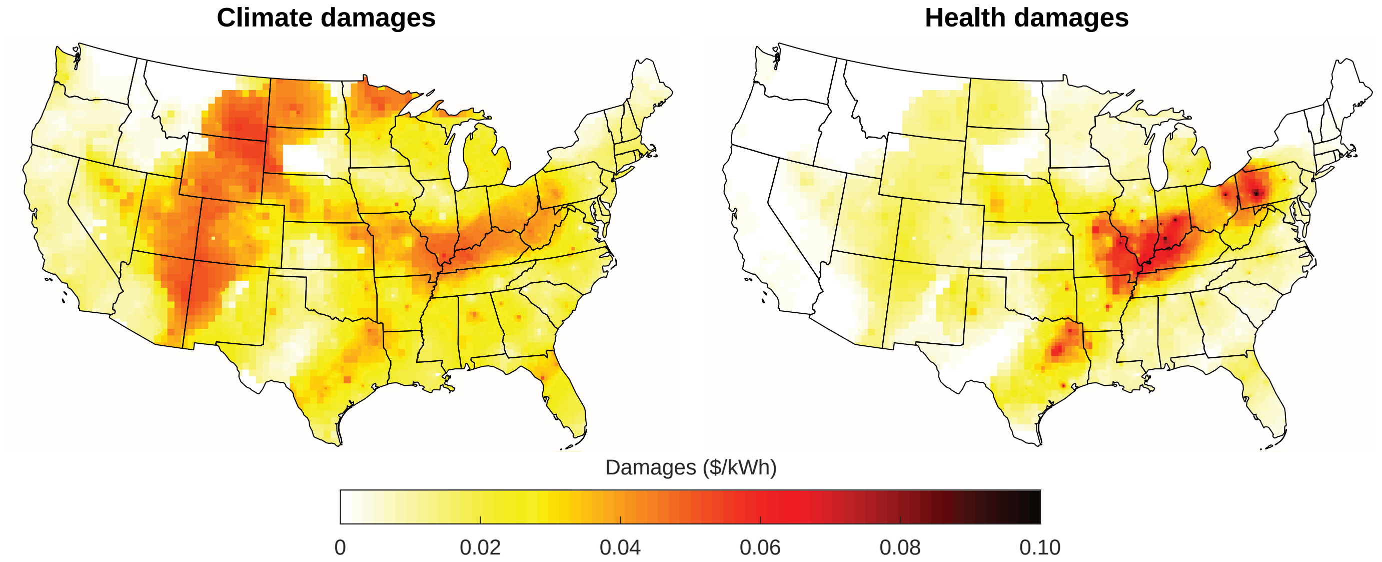

Fig. 1. Climate and health damages per kWh of electricity used in each location. The emission profile of electricity use in each location is a weighted average of the EGUs within 250 km, weighted by the inverse distance from the EGU and the quantity of electricity generated.

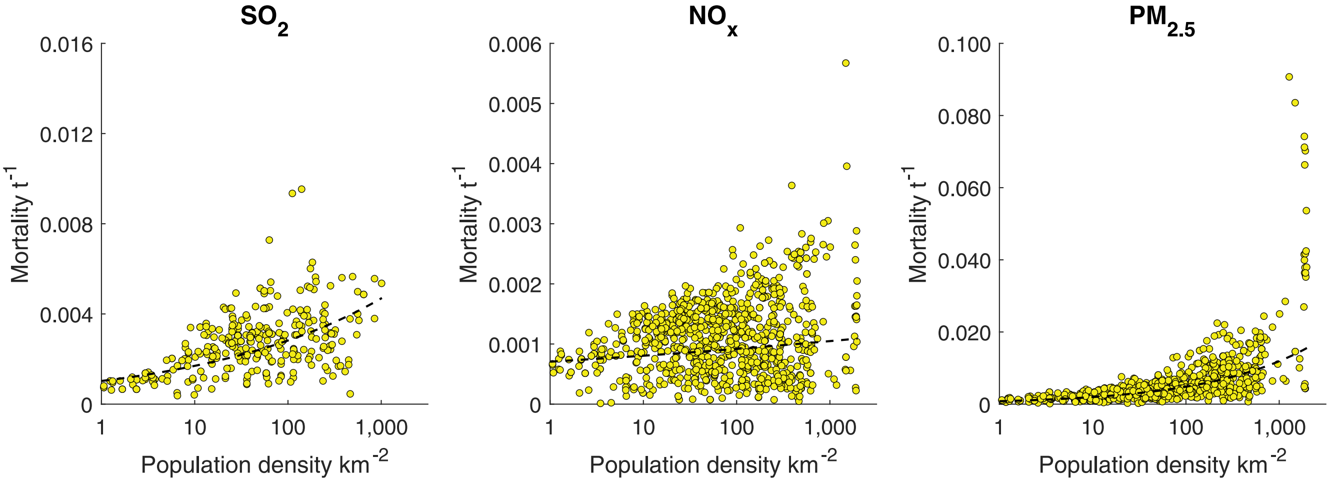

Fig. 2. Relationship between US SO_2, NO_x, and $PM_{2.5}$ electricity emission mortality impacts t^{-1} and population density in 50 km radius around emission source. Dashed lines are best-fit estimates of the data.

$PM_{2.5}$ from EGUs between China and the US (ratio: 1.8) is similar to the ratio estimated by Apte et al. [32] (ratio: 2.1) for urban emissions. We combine these results with the quantity of emissions per kWh of electricity to get mortality impacts per unit of electricity.

Next, we convert mortality and climate impacts per unit of electricity into monetary damages. Emissions of CO_2 are converted into climate damages by multiplying emissions by the SCC ($51 t^{-1}). Mortality impacts in the US are converted into health damages by multiplying estimated mortality by the EPA's recommended VSL [34] (adjusting for inflation and average income to 2018, the VSL is $11.53 million). For mortality impacts in China, we calculate health damages using a China-specific estimate of the VSL [35] (adjusting for inflation to 2018 in US Dollars, the VSL is $1.12 million). With the use of different VSLs in each country, we are making no value judgement about the relative worth of a human life between the US and China. Rather, to produce a monetary estimate of the damages we use currently available peer-reviewed studies of the observed and stated tradeoffs between risks of mortality and compensation.[10] Multiplying total climate and health damages per kWh of electricity generation by the electricity requirements to produce one cryptocurrency coin, produces an estimate of the social damages or cryptodamages per coin generated.

Using these damage estimates, for the US, we calculate the net social value of producing each cryptocurrency, for each day in our dataset (January 1, 2016 to December 31, 2018), and for any location where

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[10] For a comprehensive review of the VSL literature, and the history of use in regulatory arenas in the US and elsewhere, see Viscusi [36]. Viscusi [36] argues that more widespread use of VSLs could create a safer and more equitable society, while also recognizing that relative to the US other countries typically undervalue the risks to lives, even after accounting for income differences. Viscusi [37] recently argues that international estimates of the income elasticities of VSLs could be used for improved calibration and transfer of US estimates to other countries, after accounting for income differences. For example, doing so for Australia would more than double the current best-practices VSL estimate [37].

electricity is consumed. We define the net social value as the private benefits and costs of mining a cryptocurrency less the social damages of consuming the electricity. Specifically, the net social value of mining one coin is the price of the coin at time *t*, minus the cost of electricity in location *s* at time *t* minus the health and climate externalities of electricity in location *s* at time *t*:

$$Net\ social\ value_{s,t} = coin\ price_t - (electricity\ price_{s,t} \times electricity\ per\ coin_t) - externality\ per\ coin_{s,t} \quad (1)$$

3. Results

With the above information, we calculate the daily mortality and climate impacts and associated monetary damages of producing one coin for each of the four cryptocurrencies (BTC, ETH, LTC, and XMR) in the US and China (Table 1). Then, dividing by the market price of each cryptocurrency, we calculate the human health, climate, and total da-

Table 1
Mortality impacts, climate damages, and health damages of coin mining created by country, year, and cryptocurrency.

		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

Notes: BTC = Bitcoin, ETH = Ethereum, LTC = Litecoin, XMR = Monero. Mortality impacts associated with power plant emissions of $PM_{2.5}$, SO_2, and NO_x due to country and year-specific cryptocurrency mining activity. All damages are in 2018 US Dollars.

[a] Health damages in US calculated with $11.53 million VSL.

[b] Health damages in China calculated with $1.12 million VSL.

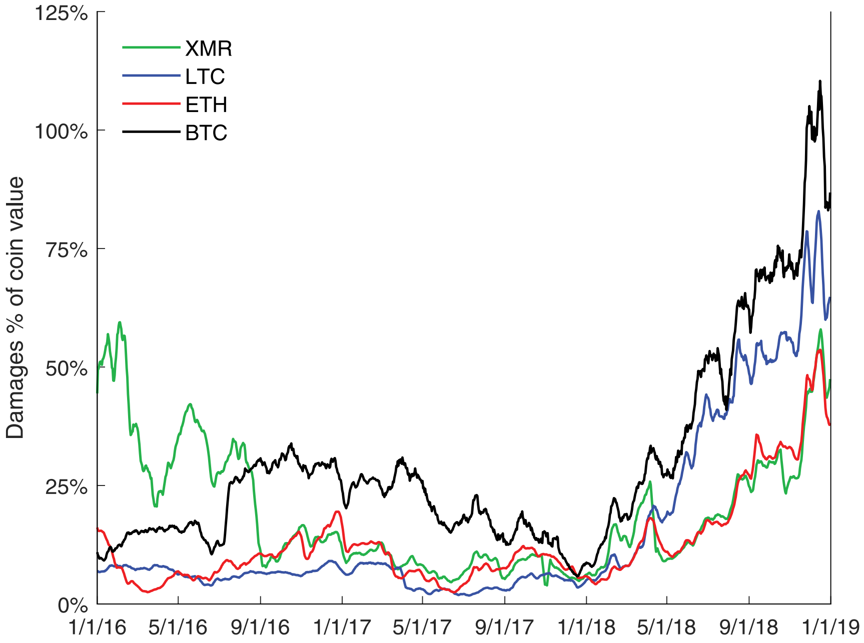

Fig. 3. Health and climate damages from producing one coin in the US as a percentage of the value of mining one coin from January 1, 2016 to December 31, 2018. *Notes:* BTC = Bitcoin, ETH = Ethereum, LTC = Litecoin, XMR = Monero.

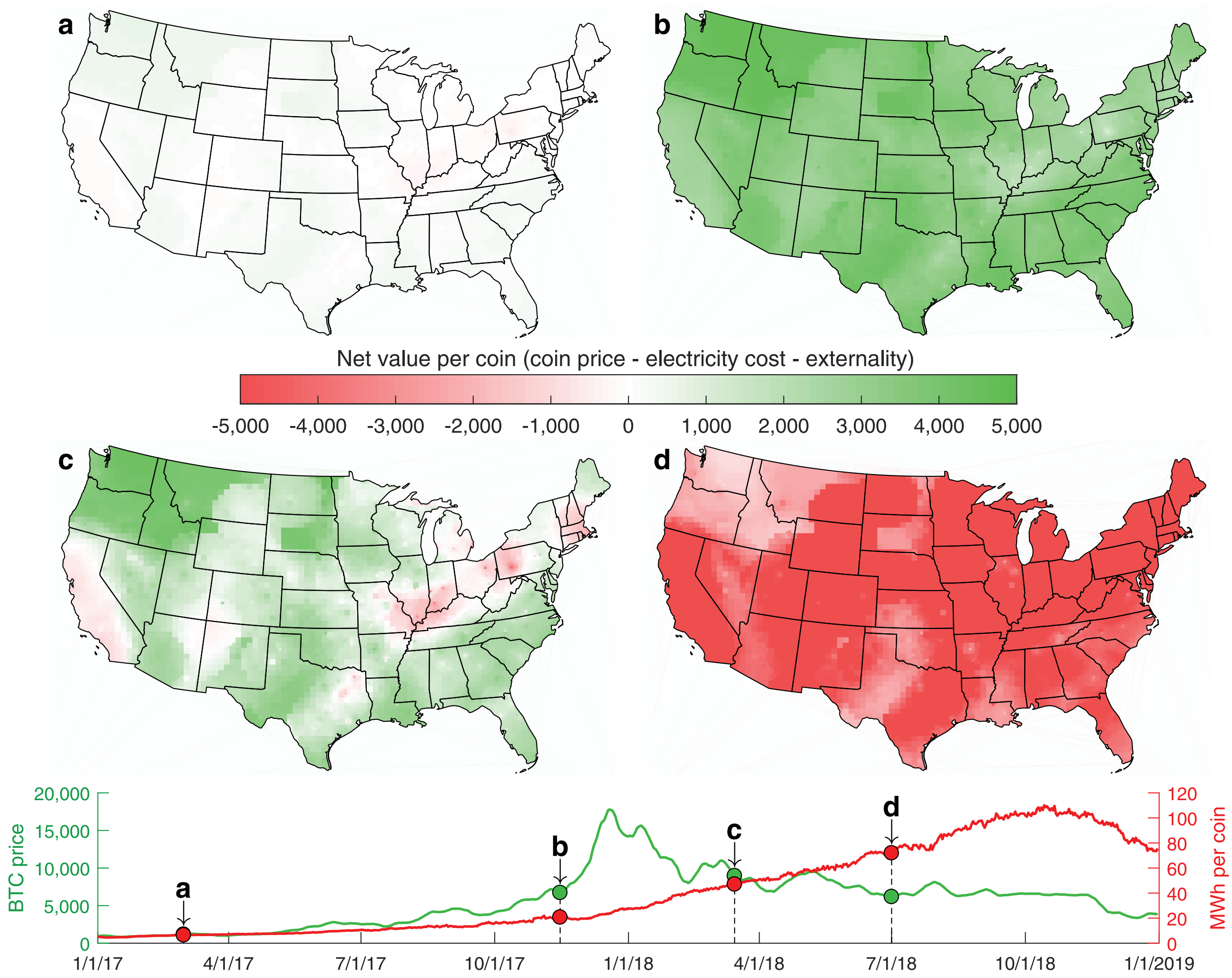

Fig. 4. Net social value of producing one Bitcoin (BTC) across time (between January 1, 2017 and December 31, 2018) and space. Panels **a**-**d** show the net value of using electricity in any location (grid cell) in the US to produce one BTC for the following dates, respectively: (**a**) March 1, 2017, (**b**) November 15, 2017, (**c**) March 15, 2018, and (**d**) July 1, 2018.

mages per dollar value of a coin mined. Fig. 3 illustrates the changing profile of total damages from cryptocurrency mining relative to the price of a coin over time in the US. The volatility of this measure is related to two factors: the price of coins and the electricity requirements to generate coins. At the beginning of our time frame, both price and electricity requirements were low, with damages averaging 21% of the value of a BTC in 2016. Then the price surged (topping out at $19,345 for BTC on December 16, 2017), reducing the damages to under 10% of the coin value. Since this date, the price of these four prominent cryptocurrencies crashed but the electricity requirements rapidly increased. As of December 31, 2018, the damages from a BTC mined in the US were estimated to be 95% of the value of the coin [BTC price on December 31, 2018: $3747; damages per coin mined: $3551 ($1480 from mortality impacts, $2071 from climate impacts)].[11] While the damages as a share of coin value were highest for BTC in 2018, producing one of the other three coins (ETH, LTC, XMR) created substantial damages, between 21 and 37% of the coin's value. For each cryptocurrency, this damage ratio increased between 2017 and 2018.

Fig. 3 shows the damages of mining a coin in the US using the average electricity mix; however, the price and damages from electricity generation will vary substantially by location and fuel source for generation. Thus, Fig. 4 examines the net social value of mining a cryptocurrency in any location in the US, accounting for the benefit and cost of generating a coin and buying electricity for the miner, respectively, and the externality costs of the electricity generation in that location borne by society (see Eq. (1)). Fig. 4 focuses just on BTC, for simplicity. It should be noted this is the *maximum* net social value, as we are excluding all other potential costs of cryptocurrency mining (e.g., equipment, cooling, or opportunity costs). Fig. 4 shows the price and electricity requirements of BTC across time, and net social value of generating a coin spatially on four specific dates: (a) March 1, 2017, when price and electricity consumption were low, and there were modest net benefits across several regions of the US; (b) November 15, 2017, when price began to surge and electricity requirements remained relatively low, leading to large net benefits to mining in almost any region; (c) March 15, 2018, when the price started to drop and electricity consumption increased, where there existed a large spatial distribution of net benefits, with positive regions in the Northwest and Southeast, and negative regions in the Midwest; and (d) July 1, 2018, when the price dropped and electricity consumption increased further, with substantial negative net benefits in almost all regions of the US.

Given the magnitude of the cryptodamages and the fact that cryptocurrency miners do not bear the full cost of the negative environmental externalities from their activities (just the price of electricity) they do not receive the correct market signals regarding when and

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[11] During December 2018, there were several days when the damages exceeded the value of the coins generated, as seen in Figure 3.

where mining can be pursued at the minimum cost to society. Presumably, miners seek locations with the lowest cost electricity. We estimate that the correlation between electricity price and damages per kWh of electricity generated (weighted by net generation) is −0.18, suggesting that the lowest priced electricity locations will generate slightly higher than average damages. If miners are more likely to locate in above-average damage per kWh locations, then our estimates using the average electricity mix (in Fig. 3) will be slight underestimates of the cryptodamages.

Available evidence indicates that a substantial share of cryptocurrency mining occurs in China [15]. We estimate that the damages of mining coins in China will be, on average, slightly smaller than in the US. Table 1 shows that for 2018, damages from a BTC coin generated in the US were 49% of the coin value, and the damages from a coin generated in China were 37% of the coin value. Emission rates (CO_2 kWh^{-1} 15% and SO_2 kWh^{-1} 16% higher) and mortality t^{-1} of emissions (SO_2 mortality t^{-1} 39% higher) are higher in China compared with the US, however, the VSL that we use in our analysis is estimated to be 90% lower. Combining these factors, the climate impacts from China cryptocurrency mining constitute a larger share of total damages (89% from climate, 11% from human health effects), compared with US damages where approximately 60% of damages are from climate impacts. It is important to note that this difference between China and the US is driven, in large part, by the difference in the magnitude of the VSL for each country.[12]

Despite the relatively similar estimate of total monetary damages per coin produced in the two countries, the mortality impacts of cryptocurrency mining are twice as high in China compared with the US. In China, for every 50,000 BTC mined (a quantity that was produced globally approximately every month in 2018) there are 12 additional deaths from exposure to particulate matter air pollution. Hypothetically, if the entire global production of the four coins we examined were produced in China in 2018, there would be ~210 deaths; whereas if all the coins were mined in the US, there would be ~100 deaths.

4. Discussion and conclusions

Given various uncertainties and weaknesses in traditional financial institutions, Nakamoto's [7] introduction of Bitcoin argued that: "What is needed is an electronic payment system based on cryptographic proof instead of trust, allowing any two willing parties to transact directly with each other without the need for a trusted third party." While there may be important social benefits connected to cryptocurrencies (an issue that we have not attempted to fully evaluate here), the focus of this analysis has been on investigating the social damages they create vis-à-vis energy use and associated air pollution emissions. For the US and China, our main finding is 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. Put differently, the human health and climate damages caused by Bitcoin represented *almost half* of the financial value of each US dollar of Bitcoin created (as represented by market prices). Further, the slightly smaller value in China relative to the US (for each $1 of Bitcoin created) occurs primarily due to the extremely large disparity between the VSL estimate for the US ($11.53 million) relative to that of China ($1.12 million), a more than 10-to-1 ratio.

If the energy demand timelines for producing Ethereum, Litecoin, and Monero follow Bitcoin, then we might anticipate similar per dollar health and climate damages in the near future. It is also clearly possible in the prescribed supply rules for a cryptocurrency that the *cryptodamages*—the human health and climate impacts—will eventually exceed each $1 value created. The above estimates ($0.49 in the US and $0.37 in China) are averaged over the year (2018); but, notably averaged across December 2018 we observed each $1 of BTC value created, generated $0.95 of cryptodamages in the US. For any cryptocurrency tied to the POW process (or something similar), the rising electricity requirements to produce a single coin leads to a situation where the price must continue rising, faster than the social costs, to maintain positive net benefits for society. Without perpetual price increases, coin mining may follow an almost inevitable cliff of negative net social benefits as the energy use required for mining increases by greater and greater amounts due to the POW process.

In exploring the social cost side of cryptocurrency mining, our analysis is restricted in some ways. For example, there may be significant negative community effects connected to mining boomtowns (e.g., see [4]) that are not accounted for here. Our analysis is limited to health and climate impacts connected to two countries, and four prominent cryptocurrencies, so in that way it may be a significant underestimate of the emergent understanding of cryptocurrency externalities. Related, our results are likely a lower-bound on actual health damages since other power plant pollutants such as mercury and cadmium (produced by coal-fired power plants), are not included in this analysis due to data limitations. Further, it should be clear that this initial, exploratory investigation of damages is: (i) restricted to a per coin basis (we make no inference about total or aggregate damages); and (ii) we do not know where coins are mined (but this might change in the future). Rather we provide an estimate of the damages *if* a coin were mined using the average emissions profile of electricity in the US and China. If "flocks" of independent crypto-miners are endogenously sorting into locations with cheap electricity, then our estimates here could be an over- or under-estimate of the social damages. As noted earlier, an example of such sorting can be seen in the Mid-Columbia Basin area of Washington State in the US, with cheap and renewable hydroelectricity [4,6]. Alternatively, many locations with cheap electricity have relatively large externalities (e.g., if they are based on coal-fired electricity).

There are several important avenues for future research: (i) theoretical modeling of mining sorting behavior; (ii) documentation and empirical estimates for geographical mining hotspots, and the spatial variability of localized pollution emissions, and impacted populations; (iii) improved understanding of the how the positive/negative net social benefits are expected to vary temporally over the life of a cryptocurrency; (iv) explorations of improved methods for accurately assessing cryptodamages, and decentralized production process in cryptocurrencies, given complicated international policy debates about the heterogeneous VSL estimates across countries (see [36,37]); and (v) theoretical and empirical evaluations of alternatives to the POW computational competition currently predominately used in the blockchain technology, which might be significantly less electricity intensive, and more capable of sustaining the net social benefits of a cryptocurrency. Narayanan et al. [38] and Vranken [39] provide excellent reviews of the properties of the many alternative mining puzzles and blockchain design alternatives, including expected energy use (see discussions of proof-of-space [5] and proof-of-stake [40], as just several of the various alternatives).

Understanding the negative environmental externalities associated with cryptocurrency mining is emerging but remains under-investigated [39,41] and we hope that this initial investigation into monetizing their impacts spurs additional research. We close by sharing our brief thoughts on policy implications of recognizing cryptodamages.

It is perhaps useful to think about the theoretical "last Bitcoin produced," or any similarly supplied POW-based cryptocurrency design. As noted in Truby [10], as the world confronts global climate change, the POW process requires ever greater computational power and energy consumption, "with no consideration of its environmental impact." Given finite supply rules, there will likely be a point before the last possible coin (or whatever the currency reward unit) is supplied

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[12] Table 1 shows that health damages per coin in China are one-fifth as large as in the US. If, however, we used the same VSL in both countries, the health damages in China would be twice as large as in the US (results available upon request).

where it is no longer privately profitable to mine (as marginal private costs exceed marginal private benefits) [5]. We argue here that the *social paradox of the last Bitcoin* is that in the presence of significant cryptodamages the socially efficient end of production may be much earlier (where marginal social costs exceed the marginal social benefits). Thus, it is in the global public interest to prevent this socially inefficient production and collectively move us away from blockchain design alternatives (i.e., POW) that are highly energy intensive.

Truby [10] provides a thorough and insightful review of the various alternative approaches, and complex regulatory and fiscal challenges for "decarbonizing" cryptocurrencies. Similar to the difficulties of addressing non-point source pollution problems,[13] cryptomining poses significant implementation challenges for designing a regulatory framework. As an alternative to restricting or prohibiting a production activity, economists often advocate for pollution taxes as one possible instrument to "internalize" otherwise unpriced and unaccounted-for negative externalities. Theoretically, such taxes could be levied in various ways (e.g., on the sale of prominently-specialized mining hardware [3], the energy use itself in known concentrated mining locales, or by somehow identifying mining profits) and via different levels of government, and there is perhaps no single preferred option [10]. Monetary estimates of the environmental damages of mining can help in calibrating appropriate tax rates.

However, the ability to locate, and re-locate, cryptomining almost anywhere (e.g., following the cheapest, under-regulated electricity source) and fund mining camps from anywhere with complete or near anonymity create significant challenges to implementing effective regulation. The anonymous production process and footloose nature of the industry is likely to ultimately require international cooperation in regulating the decarbonization of cryptocurrencies. Our concern is that delays in overcoming such regulatory barriers risk further locking in path dependence (see [42]) for the POW-based blockchain technology, which will be at odds with the urgent need for climate change mitigation [10].[14]

As an alternative to intervening in emergent cryptocurrency markets through prices (e.g., taxation) or outright restricting their development, there may be a role for government investment into R&D that focuses on designing mining puzzles that greatly reduce energy consumption (and thus production costs) while still allowing for secure validation of anonymous transactions. Fully vetting and encouraging such currency alternatives might retain the libertarian social benefits of the blockchain [10] while making "the last Bitcoin" irrelevant. Although there will still be private benefits captured from mining under possible low-energy design alternatives, as illustrated here there would be significant public good benefits (reduced cryptodamages) to justify such government investments into R&D. Importantly, such investments in R&D are not mutually exclusive with taxing to internalize cryptodamages, and may also come with the potential to generate spin-off benefits from blockchain technology more generally.

Declaration of Competing Interest

None.

Acknowledgments

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References

[1] M.J. Krause, T. Tolaymat, Quantification of energy and carbon costs for mining cryptocurrencies, Nat. Sustainability 1 (2018) 711–718.
[2] M.A. Hossin, M.S. Hosain, Bitcoin: future transaction currency? Int. J. Bus. Inf. 13 (3) (2018) 385–404.
[3] A. DeVries, Bitcoin's growing energy problem, Joule 2 (5) (2018) 801–805.
[4] P. Greenberg, D. Bugden, Energy consumption boomtowns in the united states: community responses to a cryptocurrency boom, Energy Res. Social Sci. 50 (2019) 162–167.
[5] S. Park, P. Krzysztof, A. Kwon, J. Alwen, G. Fuschbauer, P. Gazi, Spacemint: a cryptocurrency based on proofs of space, *IACR Cryptology* eprint archive, 2015.
[6] P. Roberts, This is What Happens When Bitcoin Miners Take Over Your Town, Politico Magazine, 2018 March/April. https://www.politico.com/magazine/story/2018/03/09/bitcoin-mining-energy-prices-smalltown-feature-217230.
[7] S. Nakamoto. Bitcoin: a peer-to-peer electronic cash system. (2009), URL:www.bitcoin.org/bitcoin.pdf.
[8] J. Ma, J. Gans, R. Tourky, Market Structure in Bitcoin Mining, NBER, 2018 Working Paper No. 24242. http://www.nber.org/papers/w24242.
[9] M.A. Buth, A.A. Wieczorek, G.G. Verbong, The promise of peer-to-peer trading? The potential impact of blockchain on the actor configuration in the Dutch electricity system, Energy Res. Social Sci. 53 (2019) 194–205.
[10] J. Truby, Decarbonizing Bitcoin: law and policy choices for reducing the energy consumption of Blockchain technologies and digital currencies, Energy Res. Social Sci. 44 (2018) 399–410.
[11] C. Stoll, L. KlaaBen, U. Gallersdorfer, The carbon footprint of Bitcoin, Joule 3 (2019) 1–15.
[12] M. Frankel, How Many Cryptcurrencies Are There? Motley Fool, 2018 March 16. https://www.fool.com/investing/2018/03/16/how-many-cryptocurrencies-are-there.aspx.
[13] C. Mora, R.L. Rollins, K. Taladay, M.B. Kantar, M.K. Chock, M. Shimada, E.C. Franklin, Bitcoin emissions alone could push global warming above 2°C, Nat. Clim. Change 8 (11) (2018) 931.
[14] A.M. Freeman III, J.A. Herriges, C.L. Kling, The Measurement of Environmental and Resource Values, Resources for the Future, 2014.
[15] B. Kaiser, M. Jurado, A. Ledger, The Looming Threat of China: An Analysis of Chinese Influence On Bitcoin, Cornell University, 2018 ArXiv working paperURL: https://arxiv.org/abs/1810.02466.
[16] US Environmental Protection Agency, , 2014 National Emissions Inventory, Version 2, Technical Support Document, Office of Air Quality Planning and Standards, 2018URL: https://www.epa.gov/sites/production/files/2018-07/documents/nei2014v2_tsd_05jul2018.pdf.
[17] US Environmental Protection Agency, eGRID2016 Technical Support Document, Office of Atmospheric Programs, 2018 URL: https://www.epa.gov/sites/production/files/2018-02/documents/egrid2016_technicalsupportdocument_0.pdf.
[18] B. Zheng, D. Tong, M. Li, F. Liu, C. Hong, G. Geng, H. Li, X. Li, L. Peng, J. Qi, L. Yan, Y. Zhang, H. Zhao, Y. Zheng, K. He, Q. Zhang, Trends in China's anthropogenic emissions since 2010 as the consequences of clean air actions, Atmos. Chem. Phys. 18 (2018) 14095–14111.
[19] BitInfoCharts.com, (2019), URL:https://bitinfocharts.com/.
[20] D. Krewski, M. Jerrett, R.T. Burnett, R. Ma, E. Hughes, Y. Shi, M.C. Turner, C.A. Pope, G. Thurston, E.E. Calle, M.J. Thun, Extended Follow-Up and Spatial Analysis of the American Cancer Society Study Linking Particulate Air Pollution and Mortality, Health Effects Institute, Boston, MA, 2009.
[21] C.A. Pope III, R.T. Burnett, G.D. Thurston, M.J. Thun, E.E. Calle, D. Krewski, K. Ito, et al., Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution, JAMA 287 (2002) 1132–1141.
[22] Blockchain.com, (2019), Hash Rate, March 2017-March 2019. URL:https://www.blockchain.com/charts/hash-rate.
[23] T. Lutey, Hardin Coal-Fired Power Plant Sells to Possible Cryptocurrency Company, Billings Gazette, 2019 May 1. https://billingsgazette.com/news/state-and-regional/hardin-coal-fired-power-plant-sells-to-possible-cryptocurrency-company/article_d602acfa-e3ac-5e6d-85f0-7b175f031c63.html?utm_content = bufferebe9c&utm_medium = social&utm_source = twitter.com&utm_campaign = LEEDCC.
[24] K. Pierceall, Virginia Beach Bitcoin Mining Company That Won $500,000 City Grant Files For Bankruptcy, The Virginian-Pilot, 2019 April 22. https://www.pilotonline.com/business/article_dd23979e-6514-11e9-bec0-8f0c2416333e.html.
[25] K. Torpey, Blockstream Reveals Massive Bitcoin Mining Facilities, Fidelity An Early Customer, Forbes, 2019 August 8. https://www.forbes.com/sites/ktorpey/2019/08/08/blockstream-reveals-massive-bitcoin-mining-facilities-fidelity-an-early-customer/#6db5bc6e4f3f.
[26] Interagency Working Group on the Social Cost of Greenhouse Gases. *Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis – Under Executive Order 12866* (2016). https://19january2017snapshot.epa.gov/sites/production/files/2016-12/documents/sc_co2_tsd_august_2016.pdf.
[27] C. Harvey, Should the Social Cost of Carbon be Higher? Scientific American, ClimateWire, 2017 November 22.
[28] F.C. Moore, U. Baldos, T. Hertel, D. Diaz, New science of climate change impacts on

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[13] Non-point source pollution problems refer to pollution over a large area coming from a wide variety and mix of sources, rather than concentrations generated by small numbers of easily identifiable sources (e.g., discharge pipes) that would be much easier to control or regulate. While it appears that the mining of Bitcoin and other prominent cryptocurrencies may be increasingly concentrated in pools or camps of miners with specialized hardware (e.g., see Ma 2018 [8]), the still anonymous nature of the production process leaves this difficult to pin down (but perhaps possible to eventually geographically locate [see the recent initial investigations by Stoll et al. [11]]).

[14] As of July 3, 2019, the website CryptoSlate.com [43] listed all POW-based cryptocurrencies (including leaders BTC, ETH, LTC and XMR) as holding a market share or "sector dominance" of 80.84%, among all cryptocurrencies.

agriculture implies higher social costs of carbon, Nat. Commun. 8 (1607) (2017) 1–9, https://doi.org/10.1038/s41467-017-01792-x.

[29] BP, BP Statistical Review of World Energy, 67th Edition, (2018). https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2018-full-report.pdf .

[30] A.L. Goodkind, C.W. Tessum, J.S. Coggins, J.D. Hill, J.D. Marshall, Fine-scale damage estimates of particulate matter air pollution reveal opportunities for location-specific mitigation of emissions, PNAS 116 (18) (2019) 8775–8780.

[31] C.W. Tessum, J.D. Hill, J.D. Marshall, InMAP: a model for air pollution interventions, PLoS ONE 12 (4) (2017) e0176131.

[32] J.S. Apte, E. Bombrun, J.D. Marshall, W.W. Nazaroff, Global intraurban intake fractions for primary air pollutants from vehicles and other distributed sources, Environ. Sci. Technol. 46 (2012) 3415–3423.

[33] D.H. Bennett, T.E. McKone, J.S. Evans, W.W. Nazaroff, M.D. Margni, O. Jolliet, K.R. Smith, Defining intake fraction, Environ. Sci. Technol. 36 (9) (2002) 207A–211A.

[34] US Environmental Protection Agency, Guidelines for Preparing Economic Analyses, National Center for Environmental Economics, Office of Policy, 2010 URL: https://www.epa.gov/sites/production/files/2017-09/documents/ee-0568-52.pdf.

[35] Z. Yang, P. Liu, X. Xu, Estimation of social value of statistical life using willingness-to-pay method in Nanjing, China, Accident Anal. Prevent. 95 (2016) 308–316.

[36] W.K. Viscusi, Pricing Lives: Guideposts for a Safer Society, Princeton University Press, 2018.

[37] W.K. Viscusi, Pricing lives: international guideposts for safety, Econ. Rec. 94 (S1) (2018) 1–10.

[38] A. Narayanan, J. Bonneau, E. Felton, A. Miller, S. Goldfeber, Bitcoin and Cryptocurrency Technologies, Princeton University Press, 2016.

[39] H. Vranken, Sustainability of Bitcoin and Blockchains, Curr. Opin. Environ. Sustainability 28 (2017) 1–9.

[40] P. Fairley, Ethereum will cut back its absurd energy use, IEEE Spectr. 56 (1) (2019) 29–32.

[41] J. Li, N. Li, J. Peng, H. Cui, X. Wu, Energy consumption of cryptocurrency mining: a study of electricity consumption in mining cryptocurrencies, Energy 168 (1) (2019) 160–168.

[42] W.B. Arthur, Increasing Returns, and Path Dependence in the Economy, University of Michigan Press, 1994.

[43] CryptoSlate.com (2019,) POW Cryptocurrencies. URL:https://cryptoslate.com/cryptos/proof-of-work/.