Promoting rigour in Blockchain's energy & environmental footprint research

A systematic literature review

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Agenda

1. Background
2. Our Goal
3. Methodology
4. Results
5. Code of Practices
6. Conclusion
7. Future Work

Background

Measuring energy consumption of information systems

Energy Consumption of the Internet

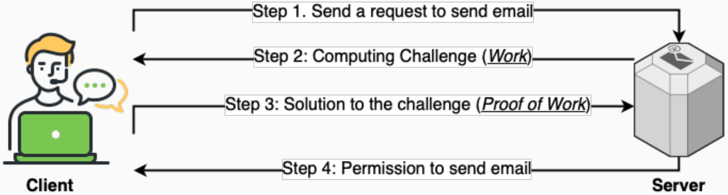
Some of the early studies suggested that up to half of the U.S. electric grid could be dedicated to powering the digital Internet economy by 2010. Empirical data has since shown this figure to be around 2% in 2010[1].

[1] Koomey, *Turning numbers into knowledge: Mastering the art of problem solving*.

Proof-of-Work

Bitcoin and other cryptocurrencies are energy hungry by design as they are based on Proof-of-Work.

- At a very fundamental level: Incentive engineering powered distributed systems consensus mechanism.



Measuring Energy footprint of an Information System

Bottom-Up

- Hardware Energy Consumption
  - Performance, Energy efficacy
- Power Usage Effectiveness (PUE)
  - Cooling, Networking etc.

$$\textbf{total} = sum(energy\_consumption\_of\_device) * PUE$$
$$\textbf{H} = sum(perfomance\_of\_device)$$

Top-Down

- Hardware:
  - Performance, Energy efficacy & *hardware composition*
- Power Usage Effectiveness (PUE)
  - Cooling, Networking etc.

$$\textbf{H} = sum(perfomance\_of\_device)^{a}$$
$$\textbf{total} = sum(energy\_consumption\_of\_device) * PUE^{b}$$

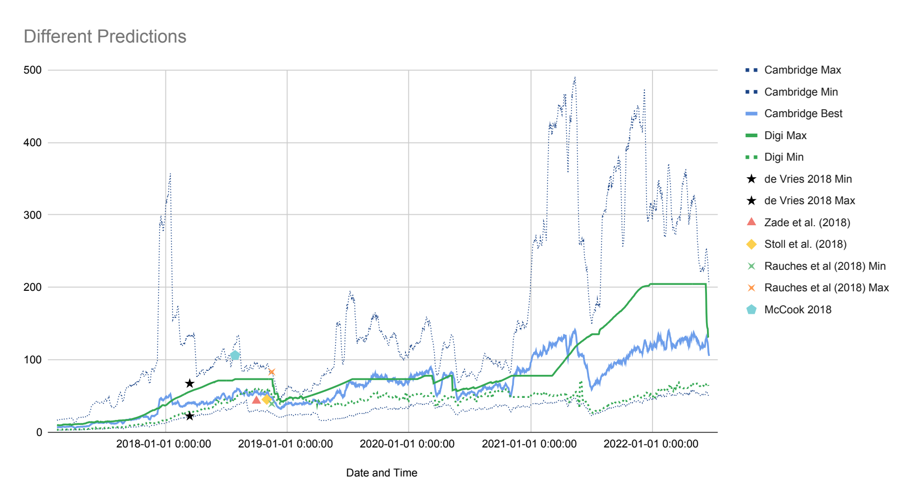
[a] Based on the hardware composition
[b] Only for hardware contributing to H

Measuring Environmental Footprint: Carbon Emissions

1. Total energy consumed by the network
2. Geographic Location of the devices in the network
3. Energy Mix[2] for shortlisted geographic locations
4. Use Energy Mix for each Geographic area to calculate CO_2 emissions per unit of electricity consumed.

[2] Primary energy used for the production of secondary sources such as electricity.

Bitcoin's Energy Consumption



Impact of assumptions on the results

Changing cost of electricity by 0.05$/ Kwh

Changing the cost of electricity in the Cambridge model from 0.05 cent/kWh to 0.10 cent/kWh will reduce the model estimate by 33TWh per year, about 36.03% or as much as Denmark's worth of electricity.

Our Goal

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All models are wrong, but some are useful.

George E. P. Box

Our Goal

Research Aim

Establish the scientific rigor of models used to estimate energy consumption or environmental footprint of distributed ledgers.

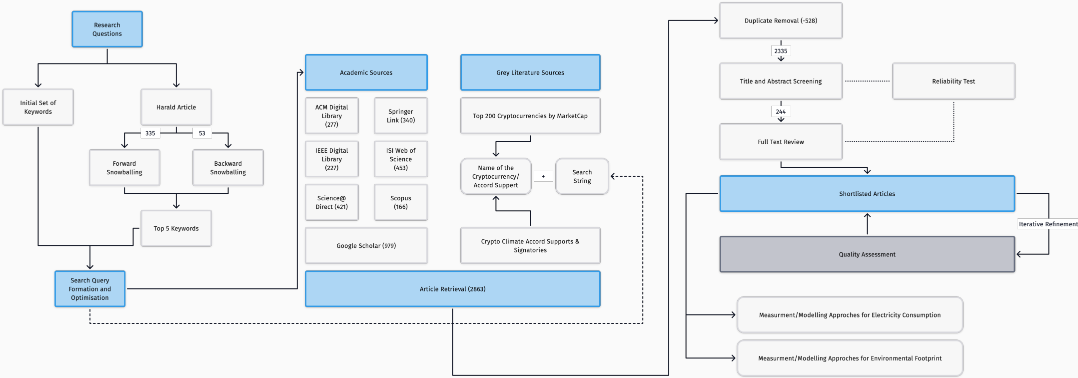
1. Categorise different research methodologies used by these studies.
2. Assess them against the code of conducts proposed by Sovacool et al.2018[3] & Lei et al. 2021[4]
3. Iteratively generate a novel code of conduct specific to blockchain energy consumption studies.

[3] Sovacool, Axsen, and Sorrell, "Promoting novelty, rigor, and style in energy social science: Towards codes of practice for appropriate methods and research design".

[4] Lei, Masanet, and Koomey, "Best practices for analyzing the direct energy use of blockchain technology systems: Review and policy recommendations".

Methodology

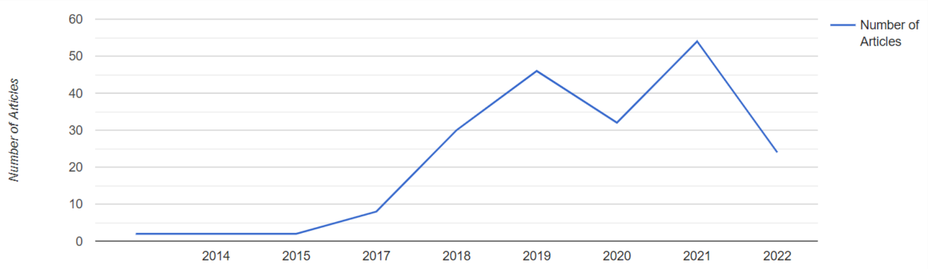
Methodology



Results

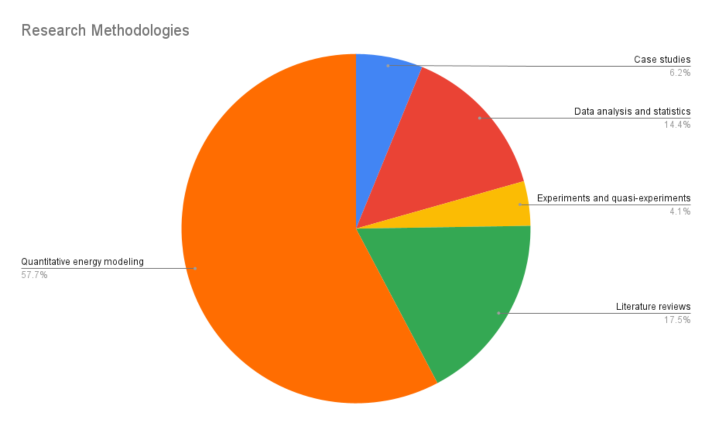
Trends in the literature

- Raising interest in the sustainability of cryptocurrencies in both academic and non-academic circles



Trends in the literature

- Most analysed studies use one of the five methodologies:



Basic Research Design

We start by assessing the studies based on their research design, specifically on the following aspects:

- Research Question
- Application of Theory or conceptual framework
- Research Design (Explicit research method, data & source code availability)
- Reliability of underlying data

Basic Research Design

1. Research Question: About 5% of the studies do not answer any specific RQ
2. Application of Theory or conceptual framework: Only 26% of studies are based on an existing theory or conceptual work
3. Research Design:
   3.1 Explicit Research method: About 34% of the shortlisted studies do not describe the research method
   3.2 Data and source code availability: 42% of studies do not share data. While 67% of studies do not share source code.
4. Reliability of underlying data: 79% of studies do not discuss the reliability of the external data used.

Results

Quantitative Energy Modelling

Critical Assessment of the literature

- We identify issues of 4 main types:
    1. Technological Issues (*hardware specification, hardware distribution*)
    2. Economical Issues (*cost of electricity, agent rationality*)
    3. Geographical Issues (*geographic distribution of participants*)
    4. Other Issues (*PUE value, reliance on unreliable sources*)

Quantitative Energy Modelling: Technical Variables

1. Constant/Static Hardware Efficiency

Assuming that hardware efficiency is constant or evolves at a set rate (*15 reviewed studies*)

2. Single/Small Number of Hardware

Assuming the network is made up of single/small no of hardware devices (*20 reviewed studies*)

3. Filling in the Missing Data

In absence of real world data, fill in values based on an assumed distribution (*5 reviewed studies*)

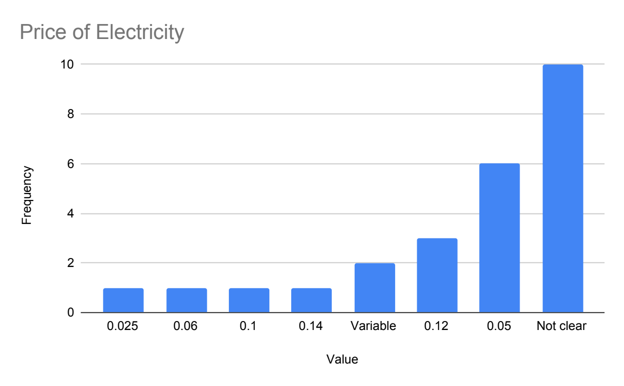
4. Random Distribution of Hardware

Assuming an arbitrary distribution of hardware usage (*4 reviewed studies*)

5. Not Accounting for Capacity Utilisation of Hardware

The operational capacity of hardware might vary from the manufacturer's advertised performance.(*7 reviewed articles* account for this)

Cost of Electricity



Hardware Lifespan

Unsubstantiated assumptions about the hardware lifespan, mostly originating from De Vries (2018). 5 reviewed studies considered hardware lifespan out of the 4 were based on the De Vries (2018) value [5].

Rational Agent based on Capex and Opex

15 of the analysed studies with an economic focus do not (explicitly) consider both Capex and Opex.

[5] De Vries (2018) assumptions have been criticized by academic and non-academic researchers.

Quantitative Energy Modelling: Geographic variables

Using mining pool server location

Using mining pool data to extract miner location is considered flawed as anyone can join a specific mining pool despite their geographic location. (8 of reviewed studies used this)

Extrapolation of location data

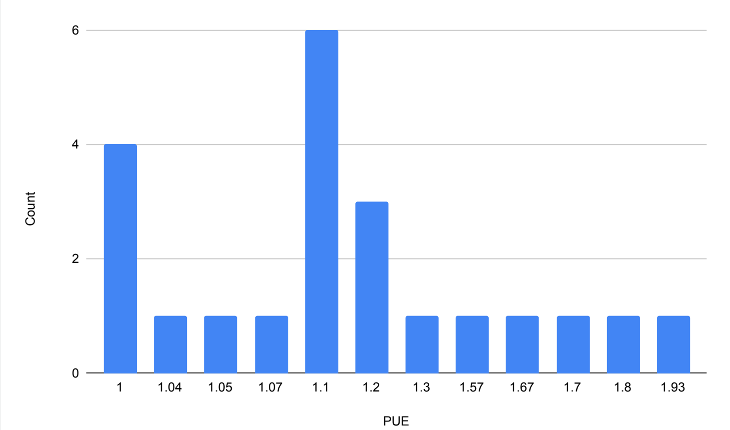
Cambridge has developed a dataset of about *32%* of the miner network in Bitcoin, some of the studies (7 in our sample) extrapolate this small data to be a represent the whole network.

Using old energy mix and carbon intensity data

Energy mix and carbon intensity data can be hard to obtain, some of the analyzed studies have used old datasets or single global values instead. (7 studies in our sample).

Quantitative Energy Modelling: Other common issues

1. PUE



Quantitative Energy Modelling: Other common issues

2. No sensitivity analysis

No analysis of the impact of variables on prediction (*8 reviewed studies*)

3. Reliance on Unreliable Sources

Using data or backing assumption without peer reviewed sources (*20 reviewed studies*)

4. Misleading Comparison

Bitcoin consumes electricity per block and not transaction (*5 reviewed studies*)

5. Black-box Elements

The source of assumption or calculation is not clear (*9 reviewed studies*)

Assessment of other methodologies

- *Data analysis and statistics*: lack of a clear hypothesis, not differentiating between statistical significance and practical significance (only 4 of 14 studies).
- *Case studies*: Lack of justification for the choice of the case study (4 of 6), not stating the boundaries clearly (4 of 6)
- *Literature Review*: Heavy focus on narrative analysis of the literature (12 of 14), lack of documentation to reproduce the article selection (8 of 12)
- *Experiments*: Small sample size (3 of 4)

Code of Practices

Basic Research Design

1. Explicit Research Methodology
2. Publicly share hardware, hardware distribution and location data:
   1. Adhere to the long term goals of Stodden et al. 2010:

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   1. Adhere to the long term goals of Stodden et al. 2010:
      1. Use version-control system
      2. Provide standardised citations for data
      3. Describe data using standardised terminology and ontologies

Quantitative Energy Modelling

1. Traceable & verifiable justification for hardware assumptions:
   1. Assumptions should be stated within the text and not in supporting material
   2. Avoid issues highlighted in the critical review, add

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   1. Assumptions should be stated within the text and not in supporting material
   2. Avoid issues highlighted in the critical review, add sensitivity analysis when filling in missing data.
2. Traceable & verifiable justification for economic assumption:

Other Methodologies

1. Data Analysis and Statistics: state clear hypothesis, use multivariate longitudinal analysis, statistically account for uncertainty of the results, acknowledge limitations of the approach used.

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2. Case studies: Choose an appropriate sample for case study and clearly define the boundary of the study
3. Literature Review: Conduct more systematic reviews
4. Experiments: Increase the sample size

Code of Practices: Basic Research Design

1. Explicit Research Methodology

2. Publicly share hardware, hardware distribution, and location data

1. Adhere to the long-term goals of Stodden et al. 2010
   1.1 Use version-control system
   1.2 Provide standardized citations for data
   1.3 Describe data using standardized terminology and ontologies
2. If using data from an existing study, supply data or a link to the data
3. Include source of data (manufacturers data sheet or actual performance validation)
4. Hardware distribution and location data should contain collection & validation steps
5. Location data should be assessed for seasonality patterns

Code of Practices: Basic Research Design

3. Share Source Code

1. *Excel Sheet*: provide details on Information Quality (IQ) and Data Quality (DQ) proposed by European Spreadsheet Risks Interest Group
2. *Software Code*: source code should be version controlled, should contain software routines that permit testing

Code of Practices: Basic Research Design

	1	2							3	
		2.1			2.2	2.3	2.4	2.5	3.1	3.2
		2.1.1	2.1.2	2.1.3						
McDonald 2021	✔	✔	✖	✔	-	✔	✔	✔	✖	✔
Gallersdoerfer et al. 2020	✔	✖	✖	✔	✔	✔	✖	✖	✖	✖
Zade et al. 2019	✔	✔	✔	✔	✖	✔	-	-	✖	✖
O'Dwyer et al. 2014	✔	✖	✖	✖	-	✖	-	-	✖	✖

Code of Practices: Quantitative Energy Modelling

1. Traceable & verifiable justification for hardware assumptions

1. Assumptions should be stated within the text and not in supporting material
2. Avoid technical issues highlighted in our critical review subsection (slide 14), add sensitivity analysis when filling in missing data.

2. Traceable & verifiable justification for economic assumption

1. Should include both capital and operational costs for different agent types (small, medium and large)
2. Cost of electricity should be as granular as possible (if data missing, use location based metric)
3. Hardware lifespan assumption should be validated using real world data

Code of Practices: Quantitative Energy Modelling

3. Collecting Geographic Data

1. Should avoid mining pool server location data, if used, should be accompanied by sensitivity analysis
2. Should avoid using grey literature, unvalidated sources for location
3. Should include the date of data collection
4. Should not extrapolate location data

4. Other Suggestions

1. PUE value should be based on empirical evidence, the modeling should include different types of agents (small, medium, and large)
2. Avoid unreliable sources of data (proven faulty studies such as Mora et al (2018))
3. Avoid using improper units of comparison

Code of Practices: Quantitative Energy Modelling

		PricewaterhouseCoopers 2021 (Tezos)	CBECI 2022	McCook 2018	Kononova et al. 2020
1	1	✔	✔	✔	✔
	2	✔	✖	✖	✖
2	1	-	✖	✔	-
	2	-	✖	✔	-
	3	✔	-	✔	-
3	1	-	✖	✖	✖
	2	✔	✔	✖	✖
	3	✔	✔	✖	✖
	4	✔	✔	✖	✖
4	1	-	✖	✖	-
	2	-	-	✔	✖
	3	✖	✔	✖	-

Code of Practices

Other Methodologies

- *Data analysis & statistics*: state clear hypothesis, use multivarient longitudinal analysis, statistically account for uncertainty of the results, acknowledge limitations of the approach used
- *Case studies*: Choose an appropriate sample for case study and clearly define the boundary of the study
- *Literature Review*: Conduct more systematic reviews
- *Experiments*: Increase the sample size

Conclusion

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- Academic studies in this field generally lack the rigor expected from academia and suffer from avoidable pitfalls
- The results from these studies should only be cautiously used as an unreliable estimate rather than as an absolute measurement
- In line with Koomey's suggestion, more real-world measured data is needed.
- Need for more transparency and standardization of the approach

Future Work

Future Work

- Apply the Code of Practices to Harald's analysis of Bitcoin
- Create an easy-to-follow template for non-academic researchers to easily construct more reliable studies for their environmental impact
- Analyze Filecoin's environmental impact while ensuring adherence to the developed Codes of Practices.
- Develop a more reliable real-time energy consumption monitoring system based on a model that complies to Code of Practice.
- We would specifically like to focus our research on:
  - Measuring: to provide methods for measuring this footprint more reliably for Bitcoin, Ethereum, and other prominent cryptocurrencies
  - Mitigating: to provide mitigation methods for reducing this footprint

Thank You

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