Leibniz ScienceCampus
Digital Transformation of Research

Interdisciplinary Colloquium on Digitalisation of Research

05.11.26 | 11:00-12:00

Measuring Ethereum's Energy Consumption for EU Reporting: A Smart Estimation Method Built Computer by Computer



Yahn Costa Hackspacher

FIZ Karlsruhe - Leibniz Institute for Information Infrastructure

Join us online

urlr.me/!ditrare-colloquium

FIZ Karlsruhe KIT Leibniz Association

DOI: 10.5281/zenodo.23728398

Measuring Ethereum's Energy Consumption for EU Reporting

A Smart Estimation Method Built Computer by Computer



Yahn Costa Hackspacher

EMAIL
Yahn.Costa-Hackspacher@fiz-Karlsruhe.de

LINKEDIN
www.linkedin.com/in/yahn-hackspacher

FIZ Karlsruhe
Leibniz-Institut für Informationsinfrastruktur
ADVANCING SCIENCE

AGENDA

Outline

0	**Introduction** What blockchains are, and where Bitcoin's and Ethereum's energy goes
1	**Regulation** What MiCAR requires, from whom, how often, and where the data comes from
2	**Existing approaches** CCRI, CCAF, Pankovska et al. and CCF: how they estimate Ethereum's energy use
3	**Our approach** A crawler-based, node-level estimation pipeline and its results
4	**Measurements** Wall-power validation on real hardware: setup, specs and results
5	**Limitations and future work** What the study cannot yet say, and what is already being addressed

FIZ Karlsruhe
Leibniz-Institut für Informationsinfrastruktur
ADVANCING SCIENCE

0

Introduction

What blockchains are, and where Bitcoin’s and Ethereum’s energy goes

0 · Introduction 1 · Regulation 2 · Existing approaches 3 · Our approach 4 · Measurements 5 · Limitations and future work

INTRODUCTION

Blockchains: what they are and what they are for

- A record book kept as identical copies on many computers [38]
- Changing an old block would mean changing all later ones [38]
- Who adds the next block?
- **Bitcoin**: computers compete to solve a hard puzzle[39]
- **Ethereum**: a validator is picked at random [41]

What it is used for

- Digital cash: Bitcoin pays people directly, no bank needed [39]
- Smart contracts: programs on Ethereum that create assets and apps [40]
- On Ethereum: stablecoins, DeFi, NFTs, games [40]
- Explored elsewhere: banking, supply chains, insurance [38]

[n] = numbered source for the statement, listed in the bibliography at the end

INTRODUCTION

Bitcoin and Ethereum energy consumption

Bitcoin: proof of work

- Miners' specialised computers (Application Specific Integrated Circuit, ASICs) running continuously [39][43]
- Every miner runs the calculation at once, but only one wins each block [39]



[50]

Ethereum: proof of stake

- Ordinary computers running node software [41]
- A randomly picked validator proposes the new block [41]
- Energy only grows with the number of nodes and their hardware [41]



[49]

FIZ Karlsruhe
Leibniz-Institut für Informationsinfrastruktur
ADVANCING SCIENCE

1

Regulation

What MiCAR requires, from whom, how often, and where the data comes from

1 · REGULATION

Why measure Ethereum's energy consumption?

- Compare the energy cost of client and hardware choices [10]
- Meet legal reporting duties in the EU [1]

Enter MiCAR

- **M**arkets **i**n **C**rypto-**A**ssets **R**egulation, Regulation (EU) 2023/1114: the EU's rulebook for crypto-assets [1]

ESMA
European Securities and Markets Authority

1 · REGULATION

MiCAR: what, how often, in which form

Mandatory [2]

- Annual energy consumption
- Sources and methodologies used to calculate it

Supplementary, above 500,000 kWh per year [2]

- Renewable energy share
- Energy intensity
- GHG emissions, Scope 1 and Scope 2
- GHG intensity

Frequency and form [2]

- Reviewed at least once a year
- Updated promptly after relevant changes
- Date of last update shown
- Public, free, plain language

Ethereum: estimate of ≈ 8 GWh per year is far above 500,000 kWh, so the supplementary indicators are in play [12]

1 · REGULATION

MiCAR: who has to disclose

Issuers

Who: create crypto-assets [1]

Example: Circle, issuer of the USDC and EURC stablecoins [34]

Disclosure: white paper (Art. 6(1), 19(1), 51(1)) [1]

Offerors

Who:

- offer a token to the public
- ask a trading platform to list it, even if someone else issued it [1]

Example: the project team behind an Ethereum-based token

Crypto-asset service providers (CASPs)

Who: provide crypto services: exchanges, trading platforms, custody, transfers [1]

Example: Coinbase [35]

Disclosure: on their own website (Art. 66(5)) [1]

1 · REGULATION

Where entities get the data

- Node operators rarely publish hardware specs
- Entities end depending on external data and estimates [11]
- Independent providers (e.g. CCRI, CCAF's CBNSI) supply network figures

What the RTS (Regulatory Technical Standards) allows when data is missing

- **Estimates** are allowed, with documented best efforts to obtain the data (Art. 6) [2]
- Method must be precise and verifiable [2]

FIZ Karlsruhe
Leibniz-Institut für Informationsinfrastruktur
ADVANCING SCIENCE

2

Existing approaches

CCRI, CCAF, Pankovska et al. and CCF: how they estimate Ethereum's energy use

2 · EXISTING APPROACHES

CCRI: measured client combinations

- Crypto Carbon Ratings Institute (CCRI)[9]
- 5 consensus × 3 execution clients x 6 hardware tiers [9]
- Node power = weighted average over the hardware tiers [9]
- Empirical backbone of CCAF, Pankovska et al. [12]
- Only public dataset with directly measured per-client power [9]



carbon-ratings.com

2 · EXISTING APPROACHES

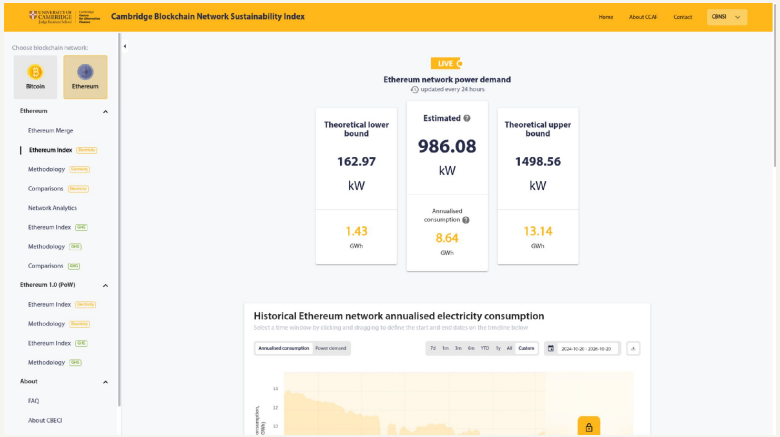
CCAF: Network Sustainability Index

- Cambridge Blockchain Network Sustainability Index (CBNSI) [12]
- Armiarma crawler (MigaLabs) identifies beacon nodes [12]
- Hardware distribution assumed from MonitorEth node counts [12]
- Per-client energy figures from CCRI [12]

Crawler: a program that contacts a node, asks for its peers, and repeats.

UNIVERSITY OF CAMBRIDGE Judge Business School | Cambridge Centre for Alternative Finance

ccaf.io/cbnsi/ethereum



2 · EXISTING APPROACHES

Pankovska et al. (2024): cloud versus home

Electricity Consumption of Ethereum and Filecoin: Advances in Models and Estimates [13]

- One of the few to separate cloud-hosted from non-cloud nodes [13]
- Instance-level power for AWS EC2 (Teads dataset) [15]
- Fixed SSD overhead of 5 W
- Cloud PUE (Power Usage Effectiveness) of 1.2 [13]

$$P = (P_{\text{pkg}} + P_{\text{RAM}} + \delta + P_{\text{SSD}}) \times 1.2$$

2 · EXISTING APPROACHES

CCF: Cloud Carbon Footprint

- Methodology to estimate cloud energy and emissions [14]
- Watts per **vCPU**, by CPU microarchitecture (SPECpower) [14]
- 0.6 W per GB **RAM**
- 1.2 W per TB **SSD** [14]
- Cloud PUE of 1.185 [14]
- Providers **without instance-level** data



cloudcarbonfootprint.org

Provider or CPU	W / vCPU
GCP	4.26
Azure	3.76
EPYC 2nd Gen	1.69
EPYC 5th Gen	8.96

2 · EXISTING APPROACHES

What existing approaches leave open

Gaps and limits, taken together

- Fleet **average** applied to every node
- **Aggregated counts**, not individual peers
- No ARM versus x86 (**Instruction Set Architectures (ISAs)**) distinction
- No **hosting** or cloud-provider classification
- Cloud modelled for **AWS** only
- No **validator** versus non-validator separation

To be a validator: a deposit of at least 32 ETH (around 64,000 EUR or 73,000 USD, October 2026) per validator [51]
Hardware: 64 GB of RAM and 4 TB NVMe SSD [51]

FIZ Karlsruhe
Leibniz-Institut für Informationsinfrastruktur
ADVANCING SCIENCE

3

Our approach

A crawler-based, node-level estimation pipeline and its results

3 · OUR APPROACH

The estimation pipeline in six steps

1
Crawl
Nebula crawler on the consensus and execution layer [18]

2
Merge and clean
Join CL and EL records per peer, drop non-mainnet peers [30]

3
Features
Client, architecture, OS, hosting provider, validator signals [20]

4
Power labels
Rule-based watts per node from CCRI, Pankovska et al. and CCF [30]

5
Random Forest
Predicts power for peers with incomplete metadata [21]

6
Validate
Compare predictions with 24-hour wall-power traces [25]

3 · OUR APPROACH

Crawl data collection and preprocessing

- Two Nebula crawler runs (Trautwein, 2023): consensus layer and execution layer [18]
- One JSONL visit record per peer
- CL and EL records **joined** by IPv4 address [30]
- Removed **non-mainnet** peers such as OP-Stack nodes [30]
- Datasets on Hugging Face, source code on GitHub [30]

Consensus layer (CL): runs proof of stake, so validators agree on the next block
Clients: Lighthouse, Prysm, Teku

Execution layer (EL): runs transactions and smart contracts and keeps account balances
Clients: Geth, Nethermind, Besu

ProbeLab
probelab.io

232,831
CL peers visited, 2026-06-19

127,911
EL peers visited, 2026-06-22

3 · OUR APPROACH

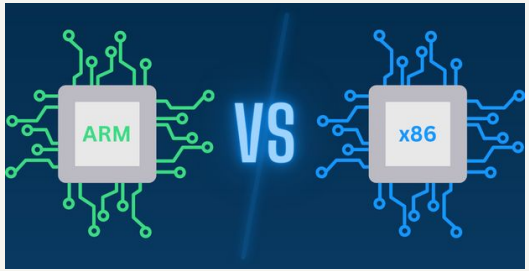
Features and validator detection

Features per peer

- **consensus_client** and **execution_client**
- **hw_arch** (ARM or x86) and **os_token** (linux, macos, windows)
- **cloud_provider**: IPv4 matched to 14 providers, no match means bare-metal
- **attnets_num** and **syncnets_num**: subnet bitvectors from the ENR [20]
- A peer counts as a **validator** if it joins **more than 2 attestation subnets**, follows extra **attestation topics**, or sits in a **sync committee** [30]

NETHERMIND

Nimbus



[52]

3 · OUR APPROACH

Power assignment: bare-metal nodes

- **x86, Linux or Windows:** average of a big and a small home PC, weighted toward the small one [9][22]
- **Macs:** the idle power comes from Apple's own specifications [24]
- **Small ARM boards (Linux):** one fixed value, taken from a Raspberry Pi that ran a node for months [23]
- **Client never measured:** it gets the value of the most similar client we did measure [30]

Consensus	Hardware 5	Hardware 6
Prysm	27.91	102.50
Lighthouse	28.18	97.01
Teku	28.36	105.63
Nimbus	27.12	95.28
Lodestar	28.93	111.72

Execution	Hardware 5	Hardware 6
Geth	34.74	125.87
Erigon	42.63	122.79
Besu	56.06	153.21

Mean total electrical power per node in watts (W). Most consuming client highlighted. Source: CCRI, The Merge report (2022) [9]

3 · OUR APPROACH

Power assignment: cloud nodes

AWS: instance-level (Pankovska et al.) [13]

$$P = (P_{\text{pkg}} + P_{\text{RAM}} + \delta + P_{\text{SSD}}) \times 1.2$$

- 8 **EC2 instances**: m6i and r6i (x86), r6g and m7g (ARM), 2xlarge and 4xlarge [13]
- Power values from the **Teads dataset** (Davy, 2021) [15]

13 other providers: CCF per-vCPU model [14]

$$P = (\text{mean}\, W_m \times \text{vCPU} + 0.6 \times \text{RAM} + 1.2 \times \text{SSD}) \times 1.185$$

- **GCP** and **Azure** use direct W per vCPU; the others use the mean over their **CPU microarchitectures** [14]

Hetzner [53]

ORACLE [54]

Vultr [55]

3 · OUR APPROACH

Random Forest for incomplete peers

- **Why use a model:**
  1. **prediction of incomplete peers**: peers that have all values ⟶ predict the value of the rest **(semi-supervised learning)** [30]
  2. **reuse**: once trained, the model can be saved and applied to any future crawl without redoing the whole pipeline [30]
- **Tool:** Python library scikit-learn (RandomForestRegressor)
- **Why Random Forest:** it works well **without much tuning**, is **hard to overfit** and is considered one of the **best for smaller datasets** [21]

Feature vector sent to the model [30]

Feature	Run 1	Run 2
hw_arch	x86	x86
os_token	windows	windows
cloud_provider	bare-metal	bare-metal
attnets_num	2	2
syncnets_num	0	0
gossipsub_att_count	2	2
consensus_client	nimbus	prysm
execution_client	geth	nethermind

FIZ Karlsruhe
Leibniz-Institut für Informationsinfrastruktur
ADVANCING SCIENCE

4

Measurements

Wall-power validation on real hardware: setup, specs and results

4 · MEASUREMENTS

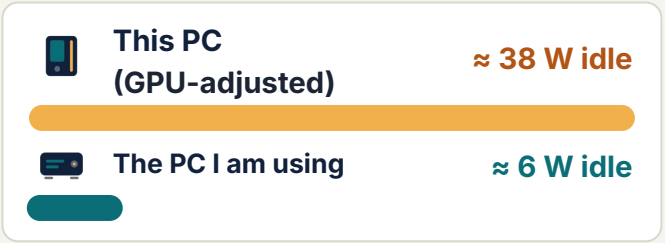
Setup: the x86 reference machine

Component	Specification [27]
System	Dell Alienware Aurora R16
Processor	Intel Core i9-14900F
Memory	64 GB DDR5-5600
Storage	2 TB NVMe system drive; 4 TB Samsung T9 USB SSD for chain data
GPU	NVIDIA GeForce RTX 4090, 24 GB (**33 W** idle draw [26])
OS	Windows 11 Home

Power metering

- myStrom WiFi Switch smart plug [28]





Note: this presentation is based on the methodology and results of the preprint (arxiv.org/abs/2610.03440). The final paper will contain much more accurate results, as we are measuring on far more suitable machines.

4 · MEASUREMENTS

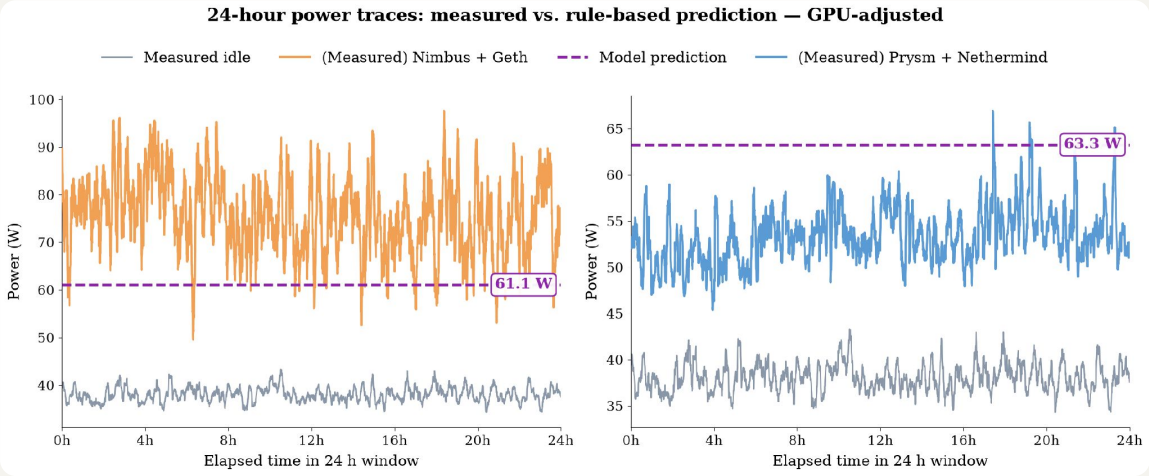
Measurement protocol

- Three 24-hour windows
- Full node on mainnet
- No validator keys
- **Nimbus + Geth**: 2026-07-11
- **Prysm + Nethermind**: 2026-07-20 to 2026-07-21
- **Idle**, no Ethereum process: 2026-07-16 to 2026-07-17



4 · MEASUREMENTS

GPU-adjusted 24-hour power traces



Nimbus + Geth

Measured (mean)	75.4 W
Estimated	61.1 W

Prysm + Nethermind

Measured (mean)	53.4 W
Estimated	63.3 W

GPU-adjusted: the RTX 4090's 33 W idle draw is subtracted from the measured wall power [26]

4 · MEASUREMENTS

Light client on a Raspberry Pi Zero 2W

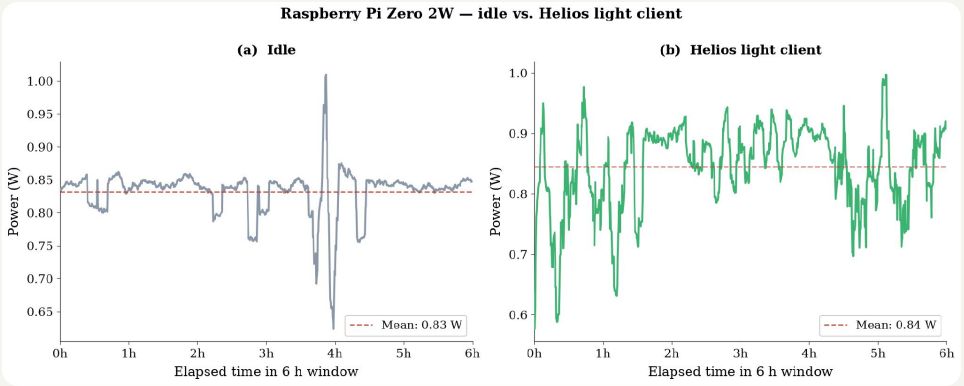
- Helios use cases: watch new blocks, look up a transaction, check any wallet's balance, estimate gas fees, read a smart contract, search token-transfer events [29]
- Quad-core Cortex-A53 at 1 GHz, 512 MB RAM, 64 GB microSD, DietPi (Debian 13) [29]
- Helios (Rust) cross-compiled on a laptop; the Pi cannot build it [29]



[36]

Idle
Measured (mean) **0.83 W**

With Helios
Measured (mean) **0.84 W**



FIZ Karlsruhe
Leibniz-Institut für Informationsinfrastruktur
ADVANCING SCIENCE

5

Limitations and future work

What the study cannot yet say, and what is already being addressed

5 · LIMITATIONS AND FUTURE WORK

What is still open, and what is already in progress

Limitations

- Single snapshot and done in different days: CL crawl 2026-06-19, EL crawl 2026-06-22 [30]
- Six clients rely on proxies [30]
- Validation on a x86 Windows gaming desktop [30]
- Static IP-range lookup; crawling from Germany inflates Hetzner and OVH [30]

Future work, some already in progress

- Multi-platform benchmarks: x86 Linux, Raspberry Pi 5, Graviton, validator machines [23]
- Direct measurements for proxied clients (Nethermind, Reth, Grandine) [9]
- Longitudinal crawl series with Nebula [18]
- Real-time ASN-to-provider mapping via RIPE NCC [33]
- Live estimation index for MiCAR-style disclosure [1]

CONTEXT · FIZ KARLSRUHE

Intersection with FIZ Karlsruhe's areas of work

- Some activities that FIZ Karlsruhe takes part in are also related to **decentralized networks**, **validation** of automated results and research around **open code**:
  - **DCUtR study on IPFS and NAT traversal** [44]
  - **Formal-Informal Mathematical Alignment** [45]
  - **FAIR Jupyter** [47]
  - **ReproScore** [48]

FIZ Karlsruhe
Leibniz-Institut für Informationsinfrastruktur
ADVANCING SCIENCE

SOURCES

Bibliography (1/5)

[1] European Parliament and Council (2023). Regulation (EU) 2023/1114 on Markets in Crypto-Assets (MiCAR). eur-lex.europa.eu

[2] European Commission (2025). Delegated Regulation (EU) 2025/422, full act (sustainability indicators). lawplayer.com

[3] Springlex. Delegated Regulation 2025/422, Article 4: disclosure in crypto-asset white papers. springlex.eu/.../article-4

[4] Springlex. Delegated Regulation 2025/422, Article 5: disclosure by crypto-asset service providers. springlex.eu/.../article-5

[5] Quotidiano Piu. Crypto-assets: EU Commission defines sustainability indicators (summary). quotidianopiu.it

[6] Hogan Lovells. The EU's MiCA Regulation: sustainability disclosures (earlier ESMA draft). hlc.com

[7] Baker Tilly. MiCAR and ESG requirements and implementation for crypto-asset service providers. bakertilly.de

[8] Arthur Cox. MiCA and Transfers of Funds Regulation finalised (application dates). arthurcox.com

[9] CCRI (2022). The Merge: Implications on the Electricity and Carbon Footprint of the Ethereum Network. carbon-ratings.com

[10] CCRI (2024). Determining the Electricity Consumption and Carbon Footprint of Proof of Stake Networks. carbon-ratings.com

[11] CCRI. Whitepaper on MiCA sustainability-indicator methods. carbon-ratings.com

SOURCES

Bibliography (2/5)

[12] Cambridge Centre for Alternative Finance (2023, 2026). CBNSI Ethereum methodology; Ethereum After the Merge. ccaf.io

[13] Pankovska et al. (2024). Electricity Consumption of Ethereum and Filecoin: Advances in Models and Estimates. arxiv.org/abs/2407.14519

[14] Cloud Carbon Footprint contributors (2024). Cloud Carbon Footprint Methodology. cloudcarbonfootprint.org

[15] Davy (2021). Estimating AWS EC2 Instances Power Consumption (Teads dataset). medium.com/teads-engineering

[16] de Vries (2022). Ethereum Energy Consumption Index. digiconomist.net

[17] Erigon contributors (2023). Announcing Caplin: Erigon Full Consensus Layer is Now Live. erigon.tech

[18] Trautwein (2023). Nebula: A Network-Agnostic DHT Crawler and Monitor. github.com/dennis-tra/nebula

[19] AgeManning (2023). Attnet revamp: subnet backbone structure based on beacon nodes (consensus-specs PR 3312). github.com/ethereum/consensus-specs

[20] Lange (2017). EIP-778: Ethereum Node Records (ENR); libp2p contributors (2024). libp2p Identify specification. eips.ethereum.org

[21] Breiman (2001). Random Forests. Machine Learning 45(1), pp. 5 to 32. doi.org/10.1023/A:1010933404324

[22] EthStaker (2025). 2025 Staking Survey Results. paragraph.com/@ethstaker

SOURCES

Bibliography (3/5)

[23] Web3 Pi and Golem Network (2024). 200 Validators on a Single Raspberry Pi 5. web3pi.io

[24] Apple Inc. (2024). Mac mini power consumption and thermal output information. support.apple.com

[25] Lei, Masanet and Koomey (2021). Best practices for analyzing the direct energy use of blockchain technology systems. Energy Policy 156. doi.org/10.1016/j.enpol.2021.112422

[26] ServeTheHome (2022). NVIDIA GeForce RTX 4090 Founders Edition Review. servethehome.com

[27] Dell Inc. (2024). Alienware Aurora R16; Intel Corporation (2024). Core i9-14900F product specifications. intel.com

[28] myStrom AG (2024). myStrom WiFi Switch: product page. mystrom.com

[29] a16z crypto (2022). Helios light client; Raspberry Pi Ltd (2021). Raspberry Pi Zero 2 W. github.com/a16z/helios

[30] Hackspacher (2026). The source code and Hugging Face dataset. github.com/yahncosta

[31] Najmuddin and Ziar (2021), Windows versus Linux power; OKX (2025) and Pathania et al. (2025), client hardware needs. doi.org/10.31841/KJET.2022.21

[32] Sutton (2022). Exploring Eth2: Cost of Adding Validators. symphonious.net

[33] RIPE NCC (2024). RIPEstat Data API: Announced Prefixes. stat.ripe.net

[34] The Block (2024). Circle earns license to issue USDC and EURC under Europe's MiCA regulatory framework. theblock.co

[35] CNBC. Coinbase secures EU crypto license, swaps Ireland for Luxembourg as main hub. nbcnewyork.com

[36] Aufranc (2021). Raspberry Pi Zero 2 W mini review. cnx-software.com

[37] Nethermind Execution Client Team (2025). Nethermind v1.33.1: Lighter, Faster and Real-Time UI. nethermind.io

SOURCES

Bibliography (4/5)

[38] NIST (2018). NIST Report on Blockchain Technology Aims to Go Beyond the Hype. nist.gov

[39] Nakamoto (2008). Bitcoin: A Peer-to-Peer Electronic Cash System. bitcoin.org/bitcoin.pdf

[40] ethereum.org. What is Ethereum? ethereum.org

[44] Trautwein et al. (2026). Large-Scale Measurement of NAT Traversal for the Decentralized Web: A Case Study of DCUtR in IPFS. IMC '26. arxiv.org/abs/2604.12484

[47] Samuel and Mietchen (2024). FAIR Jupyter: a knowledge graph approach to semantic sharing and granular exploration of a computational notebook reproducibility dataset. arxiv.org/abs/2404.12935

[49] Liliputing. Intel Frost Canyon NUC 10 review (with Intel Core i7-10710U Comet Lake). liliputing.com

[50] Mineshop.eu. ASIC Miner Buying Guide: Best Bitcoin Mining Hardware in Europe (2025 Prices). mineshop.eu

[41] ethereum.org. Proof-of-stake (PoS). ethereum.org

[42] ethereum.org. Ethereum energy consumption (figures from CCRI). ethereum.org

[43] Cambridge Centre for Alternative Finance. Cambridge Bitcoin Electricity Consumption Index (CBECI): methodology. ccaf.io

[45] Gießing et al. (2026). Formal-Informal Mathematical Alignment through and beyond Human Annotations. CIKM '26. arxiv.org/abs/2610.31011

[46] FIZ Karlsruhe. National research data infrastructure (NFDI). fiz-karlsruhe.de

[48] Samuel et al. (2026). ReproScore: Separating Readiness from Outcome in Research Software Reproducibility Assessment. arxiv.org/abs/2605.13275

[51] ethereum.org. Solo staking. ethereum.org

[52] Reidt, T. (2023). ARM vs x86: Which architecture owns the future? Emteria. emteria.com

SOURCES

Bibliography (5/5)

[53] Simple Icons. Hetzner logo (logo image on the cloud nodes slide). simpleicons.org

[54] Devicon. Oracle logo (logo image on the cloud nodes slide). devicon.dev

[55] Simple Icons. Vultr logo (logo image on the cloud nodes slide). simpleicons.org

[56] Notebookcheck (2023). Alienware Aurora R16 launched with a redesigned case and better airflow (press image). notebookcheck.net

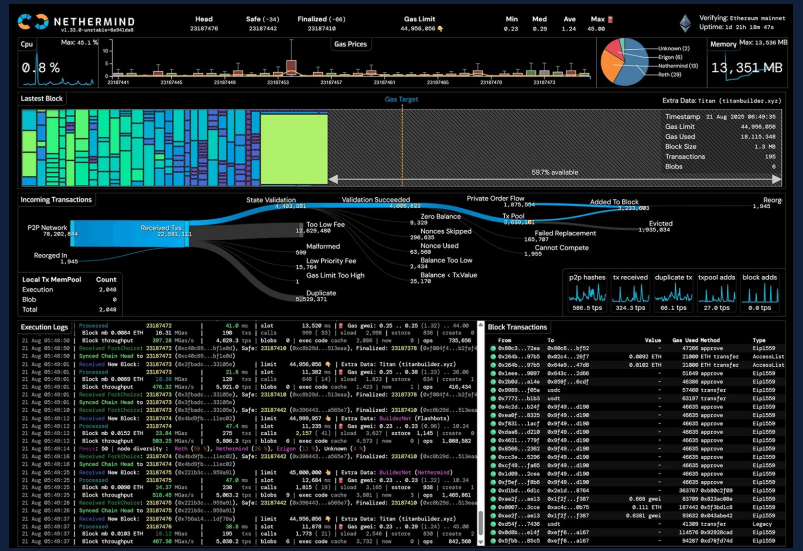
Thank you!

EMAIL
Yahn.Costa-Hackspacher@fiz-Karlsruhe.de

LINKEDIN
www.linkedin.com/in/yahn-hackspacher

DOI
10.5281/zenodo.23728398

Questions?



[37]