Study of the environmental impact of the Tezos blockchain

Life Cycle Assessment of the Tezos blockchain protocol

December 6, 2021

Final version

Study prepared for Nomadic Labs by
PricewaterhouseCoopers Advisory

pwc

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EXECUTIVE SUMMARY

Nomadic Labs (the “Company’”), French subsidiary of Tezos Foundation, has commissioned PricewaterhouseCoopers Advisory SAS - a French member firm of the PwC network of member firms, each of which is a separate legal entity - (hereinafter “PwC”) to perform a study to analyze the environmental footprint of Tezos, a public permissionless blockchain, based on a proof-of-stake protocol. This study has been prepared only for the Company and solely for the purpose agreed with PwC. PwC accepts no liability to anyone else than the Company or for any other purpose in connection with this study.

The present report aims at analyzing these impacts through a **Life Cycle Assessment[1] (LCA) approach**, in accordance with the requirements of ISO 14040 and 14044 standards.

The study is focusing on the three following **functional units** related to Tezos blockchain:

- Running a node as a baker
- Making one transaction
- Consuming one gas unit for a smart contract

The **system boundaries** include the core protocol development; embodied (production, packaging, transport, end-of-life) and use impact of bakers’ equipment to connect to the network and sign transactions; electricity consumption of Internet usage.

The calendar **year 2020 and the period January to mid-November 2021 extrapolated** to one year were studied to consider the increase of the Tezos adoption in 2021.

The analysis is based on **data collected from a panel of bakers from mid-March to end-April 2021**, from Tezos explorers, bibliographic literature and recognized LCA databases.

The following indicative results consider only the bakers’ nodes and must be considered together with the data, hypotheses and limitations detailed in this report. As an example, in 2021, **running one node for a year as a baker represents around 161 kg CO_2 eq., making one transaction on the blockchain 2.46 g CO_2 eq. and consuming one gas unit for a smart contract 2.44E-4 g CO_2 eq.**

Indicator	Unit	For the blockchain protocol		For one node		For one transaction		For one gas unit
		2020	2021	2020	2021	2020	2021	2021 (AG[2])
Greenhouse effect	kg CO_2 eq.	135,950	139,711	145	161	2.24E-02	2.46E-03	2.44E-07
Resource use, fossils	MJ	2,628,324	2,716,489	2,799	3,132	4.33E-01	4.78E-02	4.76E-06
Resource use, minerals and metals	g Sb eq.	8,025	7,506	8.55	8.66	1.32E-03	1.32E-04	1.23E-08
Particulate matter	Disease incidence	3.24E-02	3.31E-02	3.45E-05	3.82E-05	5.33E-09	5.83E-10	5.76E-14
Total primary energy	MJ	2,790,649	2,882,545	2,972	3,324	4.60E-01	5.08E-02	5.05E-06
Total electricity	MJ	948,612	997,886	1,010	1,151	1.56E-01	1.76E-02	1.77E-06

Table 1: Results summary

[1] Life Cycle Assessment in accordance with ISO 14040 does not relate to an audit or any other assurance engagement under the applicable professional standards.
[2] After Granada protocol update

With a similar number of bakers and a larger service offer in 2021 than in 2020, the impact of the Tezos blockchain for each transaction appears to lower over time. Indeed, the **energy consumption by the consensus protocol of Tezos appears not to increase proportionally with the increase in the number of transactions**.

Potential impacts are primarily due to baking equipment (about 58% of the impacts), with the exception of mineral and metal use where Internet access equipment is responsible for 55% of the impact. The use of minerals and metals is highly linked to equipment embodied impacts (around 88% of this impact), while energy-related impacts are mainly due to the use phase (78% to 86%).

The Product Environmental Footprint (PEF) methodology developed by the European Commission's Joint Research Center provides normalization factors to calculate and compare the magnitude of the contributions of potential impacts relative to a same reference unit. The normalization factors are expressed per person based on a global value. **Normalized environmental footprint results do not, however, indicate the severity or relevance of the respective impacts.**

Potential impact	**Normalization factor**		**Tezos blockchain protocol potential impact 2021 (in number of person equivalent[1])**
Greenhouse effect	kg CO_2 eq. / person	8.10E+03	17
Resource use, fossils	MJ / person	6.50E+04	42
Resource use, minerals and metals	g Sb eq. / person	6.36E+01	118
Particulate matter	Disease incidence / person	5.95E-04	56

Table 2: Normalized results in expressed in person equivalent

The influence of the electricity mix has been studied through sensitivity analyses. In the reference situation, bakers are distributed among several countries, whose specific electricity mix has been taken into account. These analyses show that the **greenhouse effect impact may vary, compared to the reference situation, from -66% assuming for example a 100% French electric mix, to +50% with an average world mix**. Other parameters influence the results up to around 50%, such as the share of network equipment allocated to baking, the energy intensity of the global Internet network, the data exchanges on the network and the share of public nodes versus private nodes.

[1] The normalization factor represents the average environmental impact of one person in the world

Limits to the study

This study has potential limitations relating to the scope studied, data collection and existing life cycle inventories in databases.

- Scope of the study
  - The study considers the impact of Tezos core protocol, and there are many applications built around the protocol which are not included in this study. For instance, the impact of end users initiating transactions or using the smart contract is not included. Therefore, as discussed in this study, the impact per service (transaction or gas quantity) of the blockchain core protocol appears to decrease with wider adoption, but there might be rebound effects due, for instance, to the development of new applications, websites or increased use of wallets.
  - The study considers nodes of bakers, due to limitation in data availability for other nodes like chain explorers, wallets and other type of services that need access to the blockchain history. One measure performed in May 2021 by the Company estimated total public nodes to be 68% higher compared to public baker nodes.
  - The end-of-life of equipment was modelled using a simplified methodology.
- Data collection
  - A large portion of the hypotheses are built on a sample of bakers addressed through a questionnaire. This sample of 70 respondents is believed to be representative of the population, but a bias might exist in the diffusion method of the questionnaire, or the typology of baker susceptible to answer this questionnaire. The average number of active bakers in 2021 at the time of this study was 411 (from January until mid-November).
  - The location of bakers' nodes is derived from the location of all the public nodes on the blockchain with the hypothesis that the distribution is similar.
  - The Company is not directly responsible for the equipment generating impact, therefore direct access to data was limited. Some data were made available by bakers during the interviews, notably on their baking set-up and data exchanges.
  - The data collected regarding internet traffic showed a correlation between blockchain activity and the quantity of data exchange. However, the uncertainty on the equation correlating the number of transactions and network exchanges remains high.
- Life cycle inventories databases
  - Most of the equipment described in this study are state-of-the-art technology. Therefore, the precise impact associated with their production remains little known. The supposed best data available and the soundest possible hypotheses were used, but the results of the model for the embodied impacts of some equipment or system, such as SSD disk and cloud computing, still contain uncertainties.

PwC has not audited or verified the information provided to them within the scope of the work, regardless of its source.

PwC cannot guarantee that PwC got to know all relevant documentation or information that may be in existence and therefore cannot comment on the completeness of the documentation or information made available to PwC. Any documentation or information brought to PwC attention subsequent to the date of this study may require PwC to adjust and qualify this study accordingly.

1. SECTION I – General Introduction

1.1. Context of the LCA study

As the digital world continues to evolve, sustainability and environmental impact has become a high priority for blockchains., Nomadic Labs (referred to as the "Company"), a French subsidiary of Tezos Foundation, sought to analyze the impacts of Tezos blockchain's operations on the environment. To that extent, the Company sought to deploy a methodology that is robust and transparent. To achieve this goal, PwC was asked to conduct a Life Cycle Assessment[1] (LCA) study, in accordance with the requirements of ISO 14040 and 14044 technical standards, recognized when analyzing the environmental impacts of a system.

Listed below is a brief description of the concepts of blockchains and Tezos. More detailed information is available in the following sections, as well as in the glossary of technical terms.

A blockchain is a tool used to exchange value quickly and securely in a decentralized manner. It is a digital ledger consisting of records called blocks that is used to record transactions, and more generally exchanges across many computers. This is especially important, as blocks cannot be altered retroactively. The shared process, secured by cryptography allows participants to verify transactions independently and relatively inexpensively. A blockchain is operated by a network of computers whose role is to broadcast transactions, and to create and validate new blocks.

Tezos defines itself as "an open-source blockchain protocol for assets and applications backed by a global community of validators, researchers, and builders".[2] Users exchange tez, Tezos underlying cryptocurrency. Applications range for example from direct payments, to loans, structured finance (decentralized finance, DeFi), or digital art. Tezos relies on a Proof of Stake algorithm, that obligates validators to leverage their tez in return for transaction validation and associated rewards. Finally, Tezos run a smart contract platform, that allows for the possibility to deploy code on the blockchain and automate transactions.

[1] Life Cycle Assessment in accordance with ISO 14040 does not relate to an audit or any other assurance engagement under the applicable professional standards.
[2] Tezos website, https://tezos.com/

1.2. Recent trends on the Tezos blockchain

This section does not aim at listing recent evolutions of the blockchain, nor at describing the most important ones. Instead, the section focuses on two recent trends that are relevant to the results of the study. The first one is the growth of the blockchain in 2021. As a result of this growth, it was decided to include the year 2021 in the report despite the year not being complete. The second one is the Granada protocol update that was implemented on the blockchain in August 2021.

Overview of the Tezos blockchain in 2021

The following graph shows the trend in the monthly number of transactions from January 2020 to October 2021.

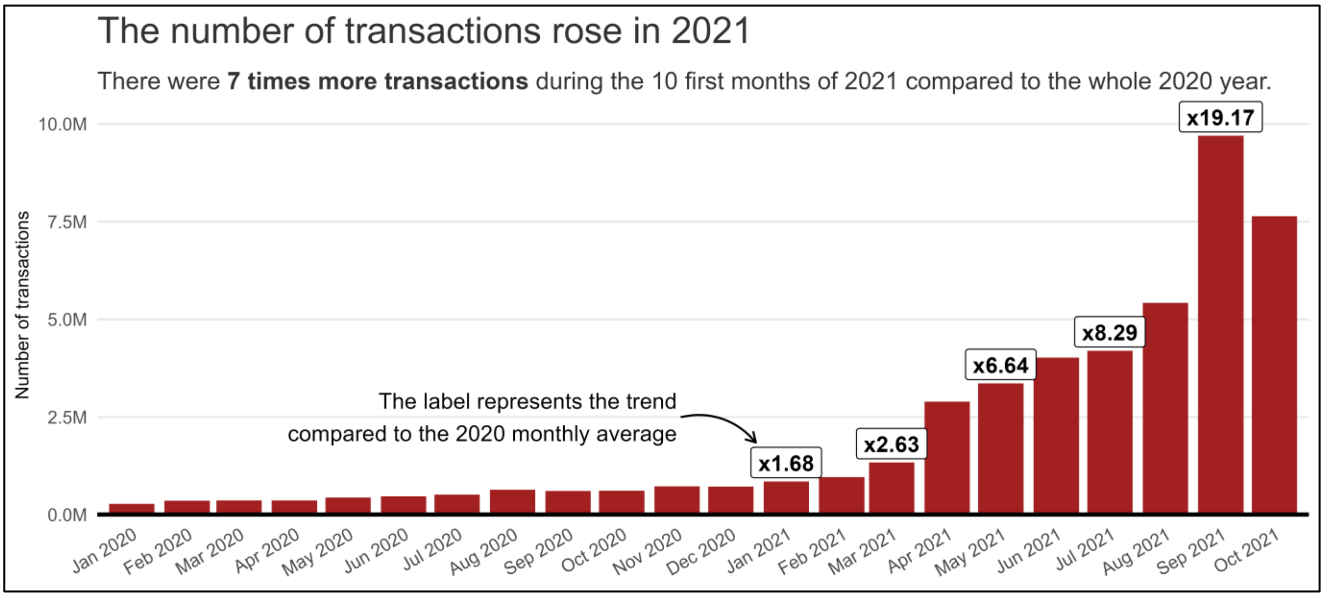

Figure 1: Trend in monthly transaction numbers on the Tezos blockchain (2020-2021)

In the month of September 2021 alone, the number of transactions was 19 times higher than the monthly average of 2020, and significantly more transactions were made on the Tezos blockchain than over the entirety of the 2020 calendar year.

The graphic below outlines gas consumption during those same months.

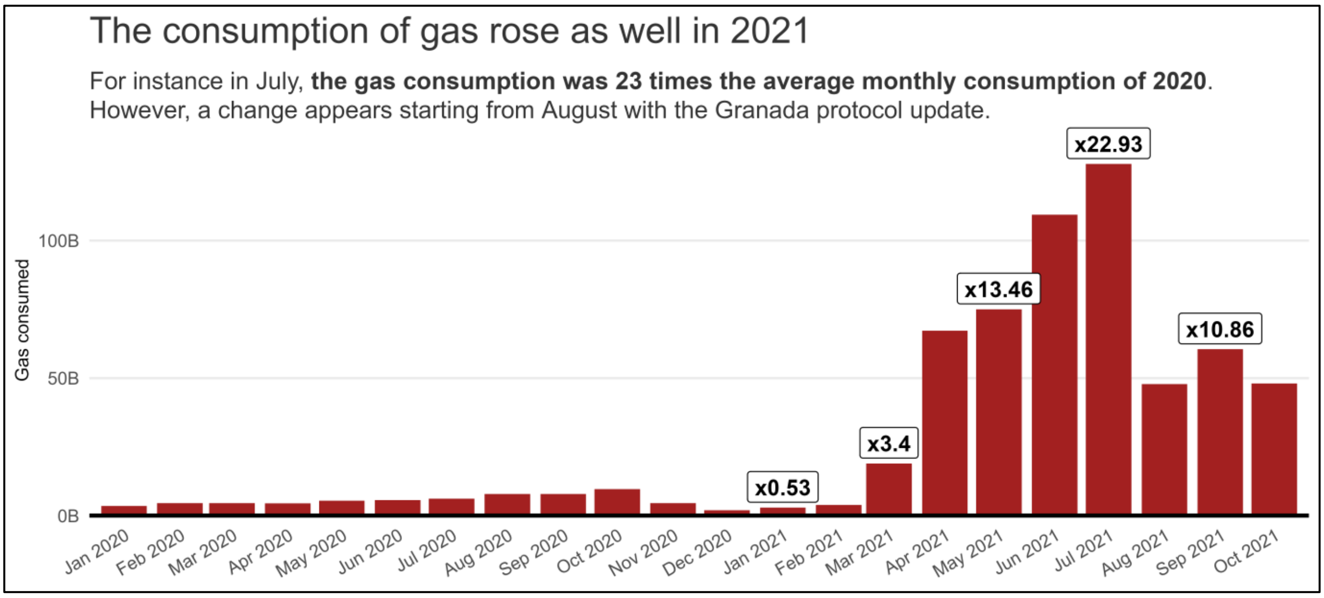

Figure 2: Trend in monthly gas consumption on the Tezos blockchain (2020-2021)

One can observe two things:

- From March to July 2021, gas consumption increased by a factor of about seven, while the transactions increased by a factor of about three.
- August 2021 presented a reduction in gas consumption -- different than the pattern observed in Figure 1. This is linked to the Granada protocol update.

Granada protocol amendment: modification of the gas cost of transactions

The protocol of the Tezos blockchain is regularly updated by new amendments, including, the Granada amendment implemented in August 2021. Within the changes brought on by this new amendment came a modification in the gas cost of operations. Gas consumption is linked to the fee amount that the baker must pay (in Tez) to realize an operation on the blockchain. This fee was reduced[1] during the protocol update, as the gas consumed by the execution of a contract was reduced by a factor of three to six. The consequence of this update for this study is that the 3rd functional unit: "consuming one gas unit for a smart contract" is not comparable before and after the Granada update.

The following graph shows the trend in the gas to transaction ratio and the effect of the update.

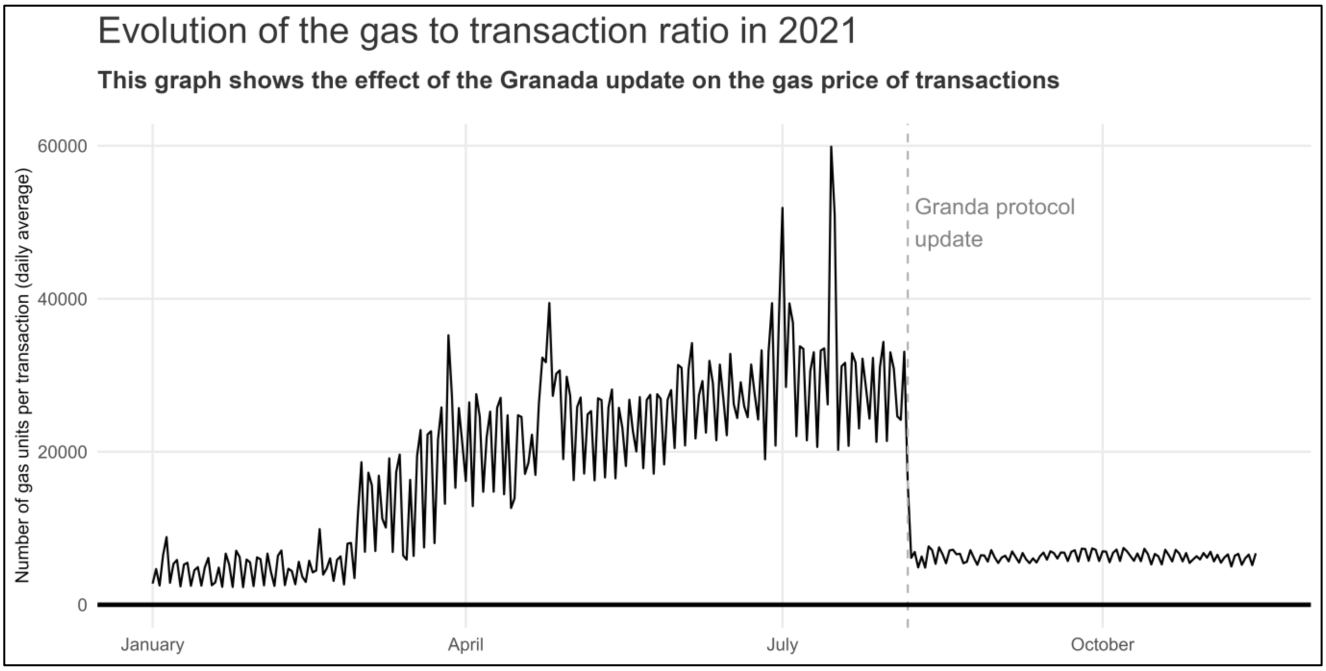

Figure 3: Gas to transaction ratio in 2021

Because of these trends:

- 2020 and 2021 were studied to calculate the LCA results, and
- the periods before and after the Granada update (August 6th, 2021) were studied to calculate the LCA result per unit of gas.

[1] Introducing Teztnets and Granada, Tezos' Seventh Protocol Upgrade Proposal
https://medium.com/tqtezos/introducing-teztnets-and-granada-tezos-seventh-protocol-upgrade-proposal-ba795eb25ca5

1.3. Goals of the LCA study

This study aims at analyzing the environmental impacts of the Tezos blockchain with regards to its main function of making transactions.

- What may be the environmental impacts of the Tezos blockchain?
- What are the main stages and substages of the life cycle causing the major impacts?
- What are the main factors that influence the impacts?

The purpose of this LCA study is to prepare an analysis on the environmental impacts of the product, which the Company will publish on its website.

This LCA study presents only potential impacts and does not predict impacts on category endpoints, exceeding thresholds, safety margins or risks.

A third-party review by an external LCA expert was also performed as explained in Section VI. Enviroconseil has been appointed by the Company.

1.4. Organization of this report

This report is organized as follows:

- Sections II and III describe the products considered, the systems studied, the nature and sources of data collected, and the assumptions used in the calculations;
- Sections IV and V present the results of the study, the sensitivity analyses and the summary of the report;
- Sections VI sets out the external critical review of this LCA;
- Section VII lists the references that are used in this report.

The appendices supplement the body of the report:

- Appendix A presents the LCA methods as set by the ISO standards;
- Appendix B specifies the sources of secondary information to model the blockchain;
- Appendix C presents the inventories of the LCA calculated during this study;
- Appendix D introduces the questionnaire sent to bakers;
- Appendix E lists the detailed comments of the critical review of the external LCA expert and their answers.

1.5. Glossary

Baker: Specific type of network peer on Tezos, who is responsible for validating, or baking, blocks.

Baking: Creation of new blocks and maintenance of a unique chain on Tezos. This process is handled by specific peers in the network, block producers, or "bakers", who are given a reward for each block that they "bake" as well as transaction fees from the network users.

Block: A set of several operations grouped together, validated by the network, and linked to the previous block of operations cryptographically. A block contains other information such as the current block number, information about the previous block, and the time at which it was validated.

Blockchain: Data structure that groups information into immutable containers called blocks, chains them together in an order-preserving way that only allows appending (but not deleting or editing). This chain of blocks (or blockchain) is replicated multiple times in a distributed (peer-to-peer) network, as every peer keeps a copy of the current snapshot of the blockchain. Registered data can stand for e.g. transactions, loans or digital art. Blockchain is also a network of exchange of data and value. In this report, the term 'operations' will be used to refer to all types of transactions. For the sake of simplicity, only public permissionless blockchains (like Tezos) will be considered and referred to as 'blockchains'.

Consensus protocol: Protocol defining the rules of validation of new blocks to form a unique chain. It is specific to each blockchain. However, there are two main families of protocols:

- Proof of Work (PoW): validators are selected based on their capacity to solve computational problems. They are called miners.
  Proof of Stake (PoS): validators are selected randomly based on their pro rata quantity of holdings in the blockchain cryptocurrency. Generally, these validators are known as "stakers", or specifically to Tezos they are known as "bakers".

Cryptocurrency: Digital currency associated with a (public) blockchain and linked to its consensus protocol.

NFT (Non-Fungible Token): Digital object on a blockchain that certifies a digital asset to be unique and therefore not interchangeable.

Node: A node is a peer (a machine, physical or virtual) on the peer-to-peer network. It keeps a copy of the current version of the chain and propagates the blocks containing all operations to the other peers. A node is not necessarily a validator (baker), but a validator is always associated with one or more nodes.

Operations: All types of transactions that can be recorded on the Tezos blockchain.

Smart contract: Self-executing contract with the terms of the agreement between parties written into lines of code, which exists on a decentralized network.

Tez: Tez is the native cryptocurrency for the Tezos blockchain.

Wallet: A wallet is a device or program that allows users to store and transfer cryptocurrency.

2. SECTION II – Definition of the scope of the LCA study

2.1. Methodology used

This report has been prepared in accordance with the methodological requirements of the following standards: ISO 14040 and ISO 14044.

Sensitivity analyses have been carried out to analyze the influence of certain hypotheses on the results of the study (see §4.34.3).

2.2. Functional units and product studied

2.2.1. Functional units

The following functional units were considered to study the environmental impacts of the Tezos blockchain:

1) Running one node as a baker
2) Making a transaction on the blockchain
3) Consuming one gas unit for a smart contract

The impact of the Tezos blockchain is determined by the development phase and the actors running nodes in a peer-to-peer network to validate, verify and record operations. The calculation for the different functional units could be the following:

1) Running one node as a baker

$$\boldsymbol{E_n = De + S + R + I + \frac{Dv}{N}}$$

Where:

$\boldsymbol{E_n}$ is the environmental impact of the average baker node on the Tezos blockchain.

$\boldsymbol{De}$ is the average environmental footprint of the device used to run the node.

$\boldsymbol{S}$ is the average environmental footprint of the equipment used to secure the node.

$\boldsymbol{R}$ is the average environmental footprint of the equipment used to access the internet.

$\boldsymbol{I}$ is the impact of the internet exchanges generated by one node.

$\boldsymbol{Dv}$ is the impact associated with the development of Tezos protocol.

$\boldsymbol{N}$ is the number of bakers' nodes on the Tezos blockchain. It is calculated as follows:

$$(Average\ number\ of\ public\ nodes\ per\ baker + Average\ number\ of\ private\ node\ per\ baker) \times Number\ of\ active\ bakers\ on\ a\ year$$

This functional unit is studied over two periods: 2020 and 2021.

The results for the **blockchain protocol** are the results of this first functional unit multiplied by the number of bakers' nodes on the blockchain.

2) Making a transaction on the blockchain

$$E_t = \frac{E_n \times N}{T}$$

Where:

E_t is the environmental impact of one transaction on the Tezos blockchain.

T is the number of transactions during one year on the blockchain.

This functional unit is studied over two periods: 2020 and 2021. The number of transactions after the 15th of November 2021 is extrapolated based on the number of transactions observed between the Granada protocol update (August 6th) and the 15th of November.

3) Consuming one unit of gas for a smart contract

$$E_G = \frac{E_n \times N}{G}$$

Where:

E_G is the environmental impact of consuming one unit of gas on the Tezos blockchain. This result can be multiplied by the number of gas unit consumed by a smart contract to get the environmental impact of the smart contract.

G is the quantity of gas consumed in a year by the blockchain.

The third functional unit: *"Consuming one unit of gas for a smart contract"* is studied over three time periods: 2020, 2021 before the Granada update and 2021 after the Granada update. Indeed (as explained in part 1.2), this cost was modified in August 2021 with the Granada protocol update. The gas cost of transactions was decreased, therefore, the gas unit before and after this update cannot be compared. The LCA results for this functional unit for 2020 and the beginning of 2021 are historical values that do not correspond to the gas as it is currently defined.

2.2.2. Technical description of the studied solution

<u>What are the different kinds of blockchain?</u>

Very different kinds of blockchains exist. Here are 2 of the most important characteristics that differ depending on blockchain platforms:

- Public vs. Private Blockchain: This feature determines whether the network allows all participants to read the blockchain and initiate transactions (public blockchain), or whether the access is restricted (private blockchain)
- Permissionless vs. Permissioned Blockchains: This feature determines whether every network participant can take part in the validation of transactions (permissionless), or whether transaction validation is restricted to a selected subset (permissioned).

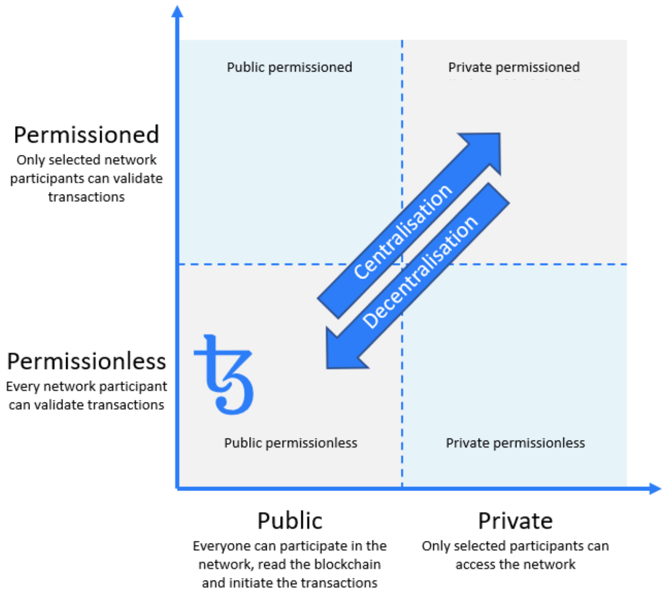

Figure 4: Blockchain definition quadrant

In the rest of the report, only public permissionless blockchains (like Tezos) will be considered and referred to as 'blockchains' for the sake of simplicity.

(Public permissionless) blockchain technologies have the following characteristics:

- They are decentralized, autonomous and deemed safe.
- They are transparent as every peer has access to all the information.
- They aim to be a safe and permanent storage of information: as blocks cannot be edited or deleted because of their chain cryptographic construction, and the entire chain cannot be modified unless one peer controls the majority of the network (more details below), which can be very expensive.

Participants can interact with the network using **nodes:** a node is a peer on the peer-to-peer network which runs a client software that propagates and stores transactions. In the blockchain world, there are two types of nodes: public nodes and private nodes. Public nodes are visible by anyone and communicate, by default, with a set of random nodes that changes over time. Conversely, private nodes are set up to communicate with a predefined and limited set of nodes, that will not change over time. Private nodes are mainly used for security purposes.

Some of these nodes only broadcast transactions, while others also play the role of **validators**. Depending on the type of blockchain, validating transactions is quite different.

The two main categories of blockchain validation protocols, describing which user is allowed to validate the next block (block *n*) are the PoW (Proof of Work) protocol and the PoS (Proof of stake) protocol. Presented below are their main features:

- In a PoW protocol, the block producer, called a miner, is selected in proportion to its capacity to solve computational problems: to make it simple, miners must find a fixed length "number" with several characteristics. To do so, they run a protocol which will generate random numbers. Having more computational capacity means being able to generate numbers more quickly, and thus having a greater chance of validating the block and receiving a reward.

  In a PoS protocol, the block producer, called staker (baker on Tezos), is selected in proportion to its quantity of holdings in the blockchain cryptocurrency.

- In a PoW context, a malicious actor must have a greater computational capacity than the rest of the network together (ca. 51% of the network total processing power) to add a malicious block; while in a PoS blockchain, the malicious actor must hold a given proportion depending on the specificities of the blockchain.

  More specifically, because of Tezos specificities and governance mechanism, there are notably 2 ways one could take control of the blockchain : one can either pass one's own amendments, which implies controlling 55% of the staking balance, but it would be publicly visible and would take about 2.5 months; or one can pass only one's own blocks, which implies controlling about 2/3 of the staking balance.

- For both protocols, currency is created when a block is validated and added to the chain of blocks. Miners or stakers earn a reward when building a new validated block (new cryptocurrency tokens are created to incentivize them to maintain the network). They also earn transaction fees, paid by the submitter of a transaction.

In summary: a blockchain aims at enabling the autonomous, provable, transparent, exchange of value and information through decentralized peer-to-peer networks formed of nodes and validators.

Tezos main features

Here are the main characteristics of the Tezos blockchain:

- A public permissionless blockchain: anyone can use the network and join the consensus to validate transactions, audit the open-source code and propose changes to it.

- A Liquid Proof-of-Stake (LPoS) based consensus: Tezos uses a PoS variant that does not limit the number of validators on the network, although a baker must hold 8,000 tez, either directly or by delegation.

- An evolutive technology using on-chain governance: Tez are also used as voting rights to decide the future evolutions of the blockchain protocol. On-chain governance makes it possible for the protocol to evolve by upgrading itself through successive amendments and to define the canonical chain.

- A platform of smart contracts: the infrastructure and core language of the compiler allows analyzing whether a code respects a set of specifications to detect bugs and potential security breaches.

Tezos high-level architecture can be represented by the following scheme, which highlights:
- The first layer, with public nodes being part of the network and private nodes, which are optionally connected to the public network. In both cases, nodes own a snapshot of the blockchain.
- On the top of this layer, a technical overlay allows interactions with the network, via smart contracts, sometimes issued by decentralized applications

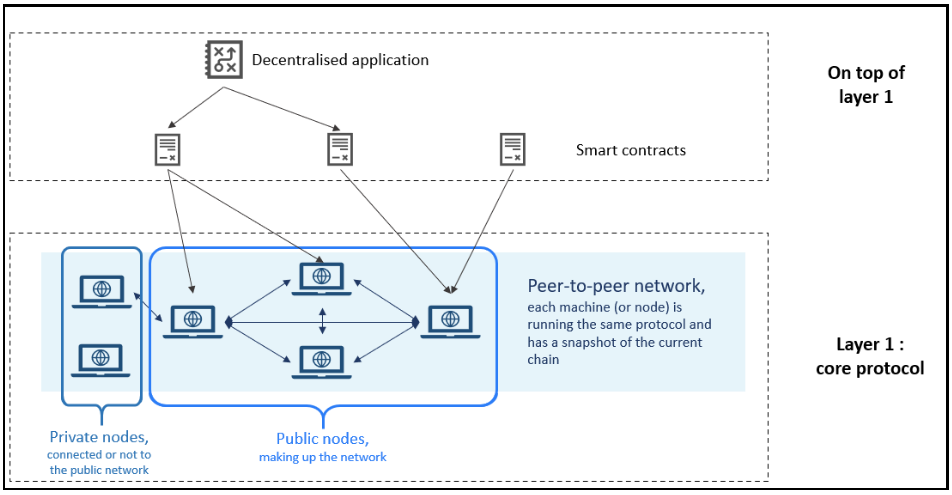

Figure 5: Tezos protocol delimitation

2.3. Scope of the studied system

The goal of this chapter is to present the studied solution, the system used to describe its lifecycle. The studied system is the Tezos blockchain core protocol.

2.3.1. Lifecycle of the Tezos blockchain

The model used to describe the solution can be categorized in two steps. The first step is the development of the software, it is a continuous process that is expected to continue for years. Therefore, this development phase is not amortized over the duration of use of the blockchain.

The second step is the use of the protocol on the blockchain. This step integrates the necessary elements to run the protocol. The devices described in the model are described with their whole lifecycle from the acquisition of raw materials to the end of life of the equipment.

Included	Not Included
Development	
• Energy consumption of developers' laptops	• Construction and energy consumption of the Company's building • Embodied* impact of developers' laptop • Marketing actions (travel, websites, etc.) • Test environment (test blockchain networks)
Blockchain running	

• Baking equipment operating on the chain
  • Embodied
    • Production
    • Packaging
    • Transport
    • IT equipment end of life
  • Use
	• Devices operating on the chain
	  • End of life of packaging
	  • Embodied impact of non-IT equipment in datacenters
	  • Construction of datacenter buildings

• Internet access equipment
  • Embodied
    • Production
    • Packaging
    • Transport
    • IT equipment end of life
  • Use
	• Internet access equipment
	  • End of life of packaging

• Internet: IP core network
  • Network usage of baking equipment (internet electrical intensity)
	• Internet: IP core network
	  • Network embodied impact (construction and maintenance of the internet)
	  • Network usage of baking-related services (explorers, snapshot providers)

*Embodied impact = impact of production, transport and end-of-life

Figure 6: Tezos protocol lifecycle

2.3.2. Delimitations of system boundaries

2.3.2.1. Delimitation rules

The following delimitation rules are applied inside the lifecycle scope defined in the previous part (§2.3.1).

To precisely delineate the systems, i.e. to decide if the production or fate of a product or material must be taken into account, a systematic rule has been used in this project:

1. For the production and transport of a consumable:

   - if the data is available to PwC, provided by the client or via LCA databases, the production of the said consumable are systematically taken into account, even if the quantity consumed is low;

   - otherwise, the inclusion threshold is set at 5 %. This means that the sum of the inputs whose production is not included in the system represents less than 5% of the total mass of the system inputs.

2. For the fate of a co-product or waste:

   - if the data is available, it is taken into account;

   - otherwise, the end of life of the product is not taken into consideration.

2.3.2.2. List of excluded lifecycle stages

The Tezos blockchain is integrated in a crypto-currency ecosystem with shared services like wallets or exchanges. Those shared services are not part of the study.

The Tezos blockchain is an ecosystem with applications and websites built around it. These other solutions built upon Tezos core protocol are not part of this study. In particular, the study is built around the number of nodes operating on the chain. The results presented in the study only take into account nodes run by bakers, which are the nodes most essential to the execution of the protocol. One baker (the person) can run several nodes, especially for data security reasons. Other agents are also running nodes on the chain, and this report provides some information on their potential number in §3.1.1. They were excluded from the study because there is no way to count the total number of private nodes operating on the blockchain and little information was available on their uptime.

In addition, some activities are excluded from the system boundaries:

- Test networks of the blockchain
- Embodied impact of developers' laptops
- The Company's marketing activities (travel, printing, websites)
- The Company's buildings energy and consumables consumption
- Nodes not operated by bakers on the Tezos blockchain
- Online services for bakers: providers of snapshot, blockchain explorers
- End-of-life of packaging
- End-of-life of the racks in data centers
- Embodied impact of non-IT equipment in data centers

In accordance with ISO 14040, certain categories of operation may be excluded from the systems on condition that this is clearly stated. In this case, the buildings construction, the embodied impact of building the internet network and non-IT infrastructure in datacenter are excluded (justified in §3.2.2.3). Indeed, stabilized operation of each of these systems is assumed, i.e. the impact on the environment linked to construction and demolition of the buildings and equipment is absorbed over the whole of their period of use. According to LCA market practice, these impacts on the environment are negligible compared with those linked to operation and would not be significant when studying the functional unit chosen for this study.

For IT equipment that were modelled for the study, landfilling was not included in the model because it is not relevant given the impact methods considered in this study. Indeed, landfilling mostly affects indicators related to water pollution as well as land occupation and transformation.

Finally, steps like packaging end-of-life, R&D, paper consumption and travel were not included. Indeed, based on LCA market practice, these steps are negligible compared to the other operational steps and would not be significant when studying the functional unit chosen for this study.

2.3.3. Allocation procedures for co-products

In accordance with ISO 14044, inputs and outputs shall be allocated to the different products according to clearly stated procedures. The LCA study identifies the major processes shared with other product systems and deals with them according to the stepwise procedure presented below.

Step 1: wherever possible, allocation should be avoided by

1. Dividing the unit process into several sub-processes
2. Expanding the product system to include the additional functions related to the co-products.

Step 2: where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products in a way that reflects the underlying physical relationships between them.

Step 3: where physical relationships alone cannot be established or used, other relationships between them should be used.

Some equipment necessary for the baking activity, such as an internet router, are also used in other activities. The internet routers in the home of bakers were allocated to the blockchain activity based on an estimation of time-of-use (cf. §3.2.2.2).

For the device running the node, even though some bakers reported using the device for other activities, they were a minority. Therefore, the equipment was entirely allocated to baking.

Finally, when a node is running in a data center, it is only using part of a server that is shared between different applications. Therefore, the embodied footprint, the electrical consumption of the server and the associated non-IT equipment are allocated based on the share of the server used by the node. This share is determined by the share of the server vCPU and RAM dedicated to this task.

2.4. Environmental flows and life cycle impact indicators studied

2.4.1. Environmental flows and energy indicators

The environmental flows linked to the studied system have been evaluated (e.g. consumption of resources, emission of pollutants to air, ground and water)

In addition to these environmental flows, the following energy indicators have been calculated:

- Total primary energy consumption (MJ): This indicator shows the amount of primary energy consumed during the life cycle of the solution, both renewable and non-renewable. The amount of primary energy is measured in MJ. Primary energy is an energy form found in nature that has not been subjected to any human engineered conversion process.
- Total electricity consumption (MJ): This indicator shows the amount of electricity consumed during the solution lifecycle. The amount of electricity is measured in MJ.

2.4.2. Environmental life cycle impact indicators

The impact methods used define the way each input or output flow is responsible for an impact. Each flow is affected to a coefficient for each method (e.g. emissions of methane converted into CO_2 eq. for the "greenhouse effect" impact). Thus, the choice of these methods has an impact on the results.

The following impact indicators are calculated and analyzed based on the environmental flows. The selection of impacts to study was done based on the Product Environmental Footprint Category rules for IT equipment (Storage)[1][2].

[1] « Product Environmental Footprint Category Rule: IT equipment (Storage) ». 2020. PEFCR. European Commission. https://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_ITequipment_Feb2020_2.pdf.

[2] The characterization factors for the impact methods can be found here: https://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml

Impact indicator	Field	Method
Resource use, minerals and metals This indicator relates to the environment depletion in mineral resources. Living resources and theirs impacts are excluded, such as extinction of species or loss of biodiversity. Calculation is based for a given resource on its extraction rate and estimated global remaining stocks. Resource use of minerals and metals is expressed in g Sb eq.	RESOURCES	Product Environmental Footprint 3.0
Resource use, fossil fuels Non-living resources are used on a daily basis to create products or energy, such as fossil fuels. The fossil fuel resource use impact method is used to assess the amount of energy from fossil fuels needed in the production process. As these resources are not renewable, their depletion has a long-term impact on ecosystems and the future of the economy. The total energy consumption from fossil fuels is measured in MJ.	RESOURCES	Product Environmental Footprint 3.0
Greenhouse effect This indicator takes into account emissions of fossil CO_2 and N_2O (these emissions coming, for example, from the combustion of fuel and natural gas) and CH_4 emissions (coming for example from the fermentation of discarded paper). On the other hand, the indicator does not take into account biomass CO_2 emissions resulting, for example, from the combustion of paper in an incinerator. Greenhouse effect is expressed in g CO_2 eq.	AIR	Product Environmental Footprint 3.0 (based on IPCC 2013)
Particulate Matter This indicator measures the adverse impacts on human health caused by emissions of particulate matter (PM) and its precursors (e.g. NO_x, SO_2). Usually, the smaller the particles, the more dangerous they are, as they can go deeper into the lungs. The potential impact of particulate matter is measured as the change in mortality due to the PM emissions, expressed as disease incidence per kg of $PM_{2.5}$ emitted.	AIR	Product Environmental Footprint 3.0

Table 3: List of selected environmental impact indicators

2.5. Requirements relative to precision, completeness and representativeness of data used

This study aims to analyze the potential environmental impacts related to the life cycle of the Tezos blockchain. In accordance with ISO 14040, requirements relative to the quality of data include the following criteria (more information on the data collection and data collected can be found in section 3.1):

	The Company	Chain explorers	Questionnaire / Baker interviews	LCA databases and bibliography
Source	• HR department • Cartographer node	• TzStats	• 7 baker interviews • 69 responses to questionnaire	• Ecoinvent 3.8: bill of materials for IT equipment, and electricity models • DEAM[1]: some packaging materials • IEA: electricity consumption of data exchange on the internet • Uptime Institute, Teads Engineering and Spec power benchmark: energy consumption of servers and data centers • Ademe: lifetime of equipment • Various: information on equipment weight and composition Details of generic modules used in the analysis are available in Appendix B
Time Coverage	2020: development of protocol 2021: location of bakers' nodes	• 2020-2021	• 2020-2021	• 1998 - 2021
Geographical representativeness	The HR data is representative of all the Company's employees and an average European electricity mix was used. The node locations acquired through the cartographer node are representative of the global situation of public nodes on the blockchain.	• Global with breakdown per country	• Global	• Raw material: global average • Assembly: China • Transport: global average • Electricity: country of use of the equipment
Technological representativeness	The data reflects average current technology			Represents the average technology over the collect period
Precision	++++ Primary data has been collected from the Company and is precisely representative of its situation.	++++ Chain explorers are reading information from the blockchain. This information is securely encrypted and cannot be altered.	++ The data is a representative sample of the baker population.	++ The data comes from databases and is representative of the year and area considered

Table 4: Quality matrix

[1] DEAM^{TM} is a PwC database to be used with the PwC LCA software TEAM^{TM}

2.6. Critical review

Hélène Lelièvre (Enviroconseil), an experienced professional around LCA, carbon footprint and eco-design, was appointed by the Company to carry out an independent critical review of the report upon completion thereof.

The critical review of this LCA is performed in accordance with ISO 14040 by an external independent expert and follows the requirements of ISO/TS 14071 standard "Critical Review processes and reviewer competencies — Additional requirements and guidelines to ISO 14044".

This expert shall not:

- be a full- or part-time employee of the commissioner or practitioner of the LCA study;
- has been involved in scoping or carrying out any of the work to conduct the LCA study at hand, i.e. I have not been part of the commissioner's or practitioner's project team(s);
- have vested financial, political, or other interests in the outcome of the study.

The LCA expert also reviewed the LCA model for this study with sample tests as stated in ISO/TS 14071.

There have been two rounds of external review, the first round took place from June to September 2021, then after an update of the study a second round was organized in October and November 2021. The comments made by the LCA expert and the responses given by PwC, are presented in section VI of the report.

3. SECTION III – Calculation of inventory: collection of data and assumptions description

This section presents the data sources specific to the LCA study and the hypotheses adopted to calculate the LCA inventories.

3.1. Data collection

Information on the lifecycle was collected from a combination of different sources. The Company provided some information, a questionnaire was sent to bakers, and several interviews were conducted with bakers.

During the months of March and April 2021, 7 bakers were interviewed including 3 personal bakers and 4 enterprise bakers. The interviewees were able to explain how they set-up their baking solution, as well as provide relevant information recorded by their device such as the server load or the internet exchanges.

A questionnaire was sent to bakers and answers were collected from March to April 2021. 70 bakers responded and 69 answers could be exploited for this study. This sample represents 17% of the average number of bakers active over 2021 (411 active bakers in average).

The complete questionnaire can be found in Appendix D, the following key information was included:

- How many nodes was the baker running?
- How many public and private nodes was the baker running?
- What type of devices was the baker using?
- What exact devices was the baker using?

The following table summarizes the sources of the data used to model the system.

Source	Data
The Company	- HR data concerning developers - Network exchanges - Bakers' location
Questionnaire / Baker interviews	- Device used - Number of nodes per baker - Network exchanges - Description of cloud or datacenter set-up
Chain explorer (TzStats)	- Number of bakers - Number of transactions - Quantity of gas consumed
LCI databases and bibliography	- Equipment power - Equipment embodied impact

Table 5: Summary of information sources

3.1.1. On the number of nodes on the Tezos blockchain

One challenging aspect of this LCA is the evaluation of the number of nodes running on the Tezos blockchain. It is a fundamental aspect of the environmental impact of the blockchain.

As explained in §2.3.2.2, the bakers or validators that were surveyed during the study are not the only agents running nodes on the blockchain. The decision was made in this study to only consider their nodes for the following reasons:

- The nodes of validators are essential to the Tezos protocol deployment. Without these nodes there could not be any exchange on the blockchain, and the security of the network won't be ensured.
- The validators can be identified and numbered thanks to chain explorers and reached through social network groups.
- On the other hand, other agents operating on the chain cannot easily be reached or numbered. Therefore, it is not possible to collect data regarding their practices and set-ups.

This limits the study to the equipment necessary to run the protocol and excludes other equipment that can add value to this protocol.

For transparency and to ensure the right interpretation of the data presented, it is important to understand what is included in the study. In addition, for transparency, here below is the detail on the information collected on the number of nodes.

Type of nodes (source)	Average number of nodes for one baker (questionnaire) [nodes]	Average number of bakers over a year (chain explorers) [bakers]		Number of nodes included in the model [nodes] x [baker]	
		2020	2021	2020	2021
Baker public nodes	1.35			601	555
Baker private nodes	0.76			338	312
Total	**2.11**	**445**	**411**	**939**	**867**

Table 6: Number of baker nodes studied

These are the nodes included in the study. These are the results of the questionnaire (average number of nodes for one baker) and the chain explorer (number of bakers).

During the study, the total number of public nodes on the network was also counted, using a software (the cartographer node) that connects from peer-to-peer to discover the network. This type of software can only record public nodes. Running for one week in May 2021, it recorded 935 public nodes (including bakers and others). Therefore, around 400 non-baker public nodes (wallets[1] and other services) are not included in the study, and an unknown number of non-baker private nodes.

[1] a wallet is a device or program that allows someone to store and transfer cryptocurrency

3.2. Life cycle

3.2.1. Development

For this step, only usage related environmental impacts are modelled. The embodied impacts of capital goods used in the development process are not included in the model (cf. 2.3.2 Delimitation of system boundaries). Therefore, the electrical consumption of developers' laptops was considered for the development phase. A European electrical mix was used to describe electrical consumption of developers' computers (see Appendix B.1).

The development is expected to continue in following years and therefore is not amortized over year of utilization of the protocol.

$$Electrical\ consumption = FTE \times Annual\ working\ time \times Laptop\ Electrical\ consumption$$

The number of FTE (full time employees) working on the Tezos protocol development is 36.5, working time for one year and one FTE is 1,744 hours.

3.2.2. Running baker's node

The impact of running nodes can be described as followed:

$$Impact\ per\ node = Impact\ equipment\ embodied + Impact\ equipment\ use + Impact\ internet\ Use$$

The equipment refers to the equipment running the node and the equipment used to access to the internet. The embodied impact is the impact associated with the raw material extraction, product processing, transportation and end of life of the equipment.

3.2.2.1. Baking equipment

According to the questionnaire bakers use the following equipment for baking:

Equipment	Share of nodes	Note
Laptop	19%	
Second-hand laptop	13%	
Raspberry Pi	10%	
Intel NUC	9%	
Other single-board computer	8%	Half of other single board computer were modelled as Raspberry Pi and half as Intel NUC.
Cloud virtual machine	12%	
Cloud physical machine	5%	
Enterprise data center	24%	

Table 7: Devices used by bakers to run nodes

The devices used by bakers to run nodes are all different kinds of computers that can run the Tezos software. The Raspberry Pi and the Intel NUC are single-board computers, which is a complete computer built on a single circuit board. Some bakers also choose to host their nodes in the cloud for increased reliability, in that case they can choose between two types of offer, a physical machine or a virtualized machine. Physical machines offer dedicated resources similar to owning a computer but is instead rented in a datacenter. Virtual machines are rented calculation resources in a virtual environment in datacenters.

According to the questionnaire bakers use the following equipment for securing their signature:

Equipment	Share of bakers	Note
Ledger Nano S (or other ledgers)	87%	
Computer	6%	Same computer used for baking
Cloud HSM	3%	
Nothing	3%	

Table 8: Security solution used by bakers

The Ledger Nano S is an HSM, a Hardware Security Module that uses cryptographic function to secure transactions and protect the signature of the baker using it. The Ledger Nano S is the most common HSM used by bakers according to the questionnaire. The cloud HSM is a HSM solution hosted in a cloud environment.

Power of the equipment:

Equipment	Power (W)	Sources
Raspberry Pi	9	Questionnaire Tom's Hardware[1]
Intel NUC	12	CNX Software[2]
Laptop	30	PwC internal study
Ledger Nano S	0.135	Ledger (calculation based on Ledger Nano X battery life, a similar device)
Router	10	SFR Box Evolution 7W Bouygues Bbox Miami 11W Livebox 2 9,6W Livebox Play 8W Freebox Revolution 17W Freebox Mini 4K 10W
Server (10% load) – Power for one node	14	Teads engineering and Spec power benchmark (see §2) of 3.2.2.3)
Cloud HSM	5.6	Teads engineering (see §2)2) of 3.2.2.3)

Table 9: Baking equipment power (W)

The details on the model of the different equipment can be found in Appendix C. The composition of the equipment and packaging is mostly based upon assumptions and not real product description from manufacturer, except for the laptop, router and computer (used to model server) that are based upon existing LCI from Ecoinvent. The embodied impact includes the impact of the different components, the transport, the packaging and the end-of-life. Based on an ADEME study[3], the lifetime considered for every IT equipment is five years

[1] Piltch, Avram. s. d. « Raspberry Pi 4: Review, Buying Guide and How to Use ». Tom's Hardware. https://www.tomshardware.com/reviews/raspberry-pi-4.
[2] « Intel NUC7CJYSAL "June Canyon" Gemini Lake NUC Mini PC Review with Windows 10 and Ubuntu - CNX Software ». 2018. CNX Software - Embedded Systems News (blog). March 2018. https://www.cnx-software.com/2018/03/14/intel-june-canyon-gemini-lake-nuc-mini-pc-review/.
[3] LHOTELLIER, Johan, Etienne LESS, Emilie BOSSANNE, Sandrine PESNEL, ADEME, et RDC ENVIRONMENT. 2018. « Modélisation et évaluation du poids carbone de produits de consommation et biens d'équipement ». ADEME.

(based on computers and laptop lifetime in the study), except for second-hand computers that have a lifetime of three years (assumption).

The usage impact is the impact of the electricity consumption of running an equipment for one year in the equipment location.

For the study, the assumption is made that devices are running 24 hours a day for the whole year. Indeed, based on the interviews conducted and the questionnaire, this is how most bakers operate. The power consumption is the average power consumption. The solicitation of the device running a node is mostly stable with one block to integrate and broadcast every minute. The action of the baker for that block (endorsing, validating or just broadcasting) is not expected to significantly influence power consumption. A peak in computing power needs occurs at the end of a cycle that happens roughly every 68 hours.

3.2.2.2. Internet access equipment: personal equipment

This part focuses on internet equipment used by bakers running their nodes from their personal home. For the details on cloud computing and enterprise datacenter internet access equipment see 3.2.2.3.

Every node has to be connected on the peer-to-peer network, therefore the internet equipment used by bakers has been modelled. The details on the model can be found in Appendix C.2.

The router used to access the internet, is used for many other purposes in addition to baking. For this study, it has been decided to allocate the router to the baking activity based on a time-of-use estimation. This is a conservative approach, as it could have been decided not to include the router at all. Indeed, the router could have had the same impact with or without the Tezos blockchain, the router would have been produced, and used without ever being turned off.

The following conservative calculation was done to allocate the router to the baker activity:

- Daily time spent online 5 hours (7 hours for United States, 5 hours and half for France and Germany) according to a study by We are Social and Hootsuite[1].
- 70% of that time using home router and not mobile network
- 2 persons in home
- Using the router 24h per day for baking

$$\frac{24}{24 + 2 \times 5 \times 0.7} = 77\%$$

The results include a sensitivity analysis for this parameter with values of 50% and 0%.

[1] We are Social et Hootsuite. « Digital 2021: Global Overview Report ». DataReportal – Global Digital Insights. https://datareportal.com/reports/digital-2021-global-overview-report.

3.2.2.3. Cloud computing and enterprise datacenter

According to the questionnaire, 17% of bakers are not hosting the node on a personal device but are using cloud services. In addition, 24% of respondents were companies that used their own data center for the node. Figure 7 represents the scope considered when studying the environmental footprint of data centers and cloud in this application.

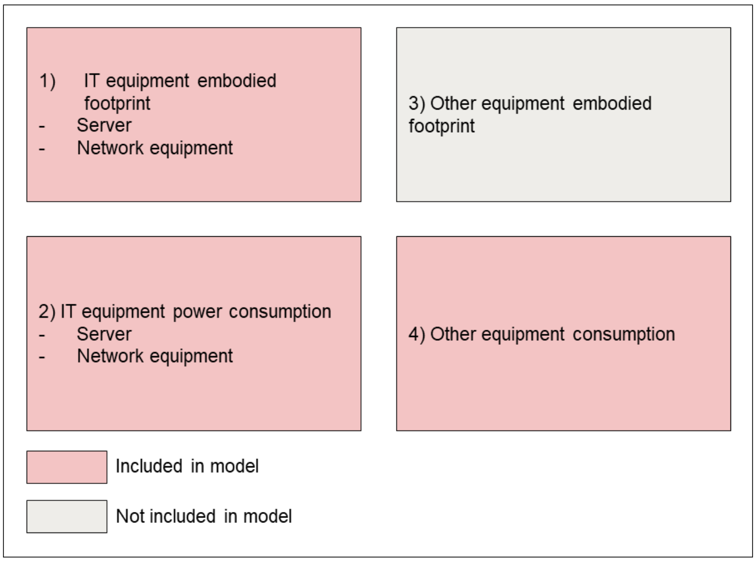

Figure 7: Scope of model for cloud and data center

1) IT equipment embodied emissions

According to the interviews, one of the largest bakers was using a 4 vCPU and 16GB of RAM cloud instance. This instance is hosted on a 64 vCPU and 256 GB of RAM bare metal server. Therefore, this instance is using 6.25% of the server.

The hypothesis for the server is to be similar to the Dell PowerEdge R7425[1], with a size 2U (U is a standard rack unit) and a weight of 40 kg (20% was added to remain conservative).

The steel frame of the rack was included in the model.

The system considers a conservative 0.9 network equipment (sum of switches, routers and firewalls) for one server based on an internal PwC study on its IT environmental footprint. The network equipment is modelled as 0.9 unit of a router, the same model of router is used for all network equipment.

2) IT equipment power consumption

Two methodologies were used to estimate the power consumption of one node running in a data center.

- An article by Teads Engineering[2] estimates the power consumption of several instances per vCPU. Based on this article the power consumption is estimated at 3.5W per vCPU under a 10% load. This load, being conservative, is superior to what was reported during interviews. This gives a 14 watts consumption for the server.

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1 Dell.com – PowerEdge R7425

2 DAVY, Benjamin. 2021. « Estimating AWS EC2 Instances Power Consumption ». Medium. March 2021. https://medium.com/teads-engineering/estimating-aws-ec2-instances-power-consumption-c9745e347959.

- The Spec power benchmark[1] is a benchmark of the power consumption profile of several servers. From the benchmark all results with server having at least 16 GB of RAM were selected. Then, of those 261 results, the average power for a 10% load and 16 GB of RAM is calculated. *For instance: if a server with 32 GB of RAM has a 30 watts power consumption under a 10% load, then the result is 15 watts for 16 GB of RAM.*
  Using this methodology the results was 13.6 watts.

Therefore, it was decided to use 14 watts as the basis for the consumption of one node running on a dedicated server in a datacenter or in the cloud.

However, some bakers use cloud services with shared resources, these shared resources mean that the cloud provider is mutualizing its client consumption to increase loads on the server. By increasing the load on the server, the cloud provider aims to achieve two goals: the first to reduce the amount of equipment required and the second to reduce power consumption (servers are more power efficient in operations per watt with an increased load). According to the Uptime Institute "Beyond PUE: Tackling IT's Wasted Terawatts"[2] (see Appendix C), the average cloud data center server operates with a 40% load (meaning 4 times as many operations per second as a 10% load) and only consumes around twice as much energy as a server operating under a 10% load. This result is also backed by the Spec power benchmark, which shows that with a 40% load a server consumes only 1.5 times as much energy as with a 10% load. Consequently, nodes in cloud server in a shared virtualized environment were modelled to be twice as energy efficient and require 25% of the IT equipment compared to a node in an enterprise data center.

The internet equipment consumption is based on the router for personal baker, with 10 watts of power. This is not a critical part of the model because there is an average 0.056 network equipment per node (0.9 per server and the equivalent of 16 nodes for one server).

Parameter	Enterprise Datacenter	Cloud – Dedicated resources	Cloud – Shared resources
PUE	1.7	1.2	1.2
Server load	10%	10%	40%
Network equipment (number for one node)	0.056	0.056	0.056
Power for one node	24.8 Watts $(14 + 0.056 \times 10) \times 1.7$	17.5 Watts $(14 + 0.056 \times 10) \times 1.2$	9.1 Watts $\left(\frac{14}{2} + 0.056 \times 10\right) \times 1.2$

Table 10: Power for one node in different datacenter infrastructures

3) Other equipment embodied footprint

The embodied footprint of non-IT equipment in the data center was not considered in the study. In the following table it is demonstrated that these equipment are not significant in the lifecycle of the Tezos blockchain regarding greenhouse effect.

1 Spec. « All Published SPEC SPECpower_ssj2008 Results ». https://www.spec.org/power_ssj2008/results/power_ssj2008.html.

2 Dr. Bashroush, Rabih, et Andy Lawrence. 2020. « Beyond PUE: Tackling IT's Wasted Terawatts ». Uptime Institute. https://uptimeinstitute.com/beyond-pue-tackling-it%E2%80%99s-wasted-terawatts.

Equipment	Carbon Footprint (kg CO_2 eq.)	Number of equipment per server	Lifetime	Maximum annual footprint for one node (g CO_2 eq.)[1]	Maximum annual footprint as share of one node footprint.
Direct and indirect cooling (water-air)	8 to 10[2]	0.05 (one equipment per rack)	10 to 15	2.98	0.002%
Cold generator (water and air)	30 to 70[2]	0.02 (one equipment for 2 racks)	10 to 15	10.67	0.007%
Electricity Generator	3,880[3]	0.01 (one equipment for 200 kW, if 25 kW per rack then one for 8 racks)	10 to 15	144	0.089%

Table 11: Data center non-IT equipment carbon footprint

For the same reason the building infrastructure of the data center is not considered, as it is amortized over a long period and would not be significant to the study.

Negligibility of non-IT equipment embodied footprint could only be measured for the carbon footprint and not for other indicators.

4) Other equipment power consumption

Datacenters need non-IT equipment to run, especially for the cooling of the servers. The power consumption of those equipment is often measured with a metric called power usage effectiveness (PUE). The PUE is the ratio of energy used by the datacenter over the energy used by the computing equipment. This metric is tracked by datacenters as a measure of their operations efficiency.

Based on the Uptime Institute: "Global Data Center survey 2020"[4], the values considered were 1.2 for cloud and 1.7 for enterprise data center. These ratios were applied to server and internet access equipment electrical consumption to get the total power consumption of a node running in those environments.

[1] The maximum annual carbon footprint of the equipment is based on the upper bound of the carbon footprint and the lower bound of the equipment lifetime.

[2] ADEME. 2012. « Technologies Numériques, Information et Communication – Guide Sectoriel ». https://www.ademe.fr/sites/default/files/assets/documents/ademe-ges-tic-0212.pdf.

[3] Ecoinvent: generator production, 200kW electrical, RER 2020

[4] Ascierto, Rhonda, et Andy Lawrence. 2020. « Uptime Institute Global Data Center Survey 2020 ». Uptime Institute. https://uptimeinstitute.com/2020-data-center-industry-survey-results

3.2.2.4. Location of the bakers' nodes

The node location was collected by the Company using a software that goes from node to node to explore the network. The software records the IP address of every node it meets, the node location is then deduced from the IP address using an API. The data collection period lasted for one week in May 2021. The location applies for the time periods studied (2020 and 2021), because there is no historic data of this location and there is no reason to believe the geographical location of nodes has differed significantly between the two periods.

The software collected the location for all nodes, including non-baker ones. This location was applied to the bakers' nodes using the same distribution.

Mix	Share
United States	27.19%
Germany	19.10%
France	9.21%
Finland	6.07%
Ireland	5.84%
Rest of the World	5.17%
Japan	4.94%
Canada	4.94%
EU-27[1]	3.82%
Singapore	3.60%
Switzerland	2.47%
Netherlands	2.25%
Hong Kong	1.80%
United Kingdom	1.35%
Russia	1.12%
China	0.67%
Austria	0.45%

Table 12: Node location for electricity mixes

Electricity mix data is not available for all countries returned by the API requests. For these countries, a generic mix of the European Union, if the country is a member, or a world mix was applied. Every country holding more than 2% of the nodes was represented using its country mix.

This electrical mix is applied to the devices running nodes (equipment and internet access). In total, 91% of these devices have a country mix, 4% have an economical area mix (EU-27) and 5% have a world mix.

[1] EU-27 includes the European Union countries not listed elsewhere (i.e. excludes Germany, France, Finland, Ireland, Netherlands and Austria).

3.2.2.5. Internet use

Node internet usage

The nodes are connected to each other and communicate over the internet, which generates electricity consumption.

There are two types of nodes on the blockchain: public and private nodes. Public nodes will by default communicate with 50 other nodes. The peers of a given node are not chosen by the node itself, it is rather a random set of peers that will be updated over time. Oppositely, private nodes are set up to communicate with a limited number of other nodes that may not change over time. They are used by bakers for security purposes.

Consequently, internet usage is very different for a private and a public node. The private node is only listening to a few other (sometimes one) nodes, whereas the public node is exchanging by default with 50 other nodes.

To estimate the yearly network traffic of a node, the network traffic of three different bakers (5 nodes) was analyzed. The bakers either volunteered to give more information when responding to the questionnaire or were contacted by the Company:

- One baker, contacted by the Company, provided data over a one-month period over April and May 2021 and over eight days in October 2021.
- One interviewed baker provided data for its 2 public nodes and its private node over one month in March/April 2021 and one month in September/October 2021.
- Another interviewed baker provided data points for two long periods: 454 days from the 2020-01-25 to the 2021-10-14 and 187 days from the 2021-04-23 to the 2021-10-28.

Two conclusions could be drawn from these three data sources:

- Network exchanges can vary significantly from one node to the other. One node can have around four times higher internet usage compared to another over one year.
- Network exchanges have significantly increased from April 2021 to October 2021. This suggests that internet usage is correlated to blockchain activity.

The following table states the observed correlation between transactions and data exchanges (data exchange is the average of upload and download).

	Data per transaction (KB / transaction)	Data fixed (GB / day)
	Data is the average of input and output	
Baker 1 - public node	5.3	NA
Baker 2 – public node	3.125	0.58
Baker 3 - public node	17.3	1.47
Public node - Average value	**8.575**	**1.025**
Baker 2 – private node	0.365	0
Private node - Average value	**0.365**	**0**

Table 13: Data collected from bakers on internet usage

There is a large uncertainty regarding this average value for the relationship between transactions and data exchanges, as evidenced by the fact that the data per transaction for the "Baker 3" is more than 5 times higher than for the "Baker 2". There is also a large uncertainty over data exchanges from private nodes, with only two data points from one baker. However, with a limited impact as, with this estimation, the data exchanges of a private node represent between 0.5% and 2.5% of the one of a public node (cf. Table 14).

The network traffic was estimated using the average of download and upload to avoid double counting, as this is a peer-to-peer network. A sensitivity analysis was performed on the quantity of data exchanged by public nodes (see 4.3.4).

This table presents the average internet traffic generated by one node over the different periods studied with the details of the calculation:

Row	Node	unit	2020	2021	Trend
(1)	Number of transactions	unit	6,066,719	56,776,617	836%
(2)	Data per transaction (public node)	KB	8.575	8.575	-
(3)	Data per transaction (private node)	KB	0.365	0.365	-
(4)	Data exchanges variable part (public node) $[(1) \times (2) \times 10^{-6}]$	GB	52	487	836%
(5)	Data exchanges variable part (private node) $[(1) \times (3) \times 10^{-6}]$	GB	2.21	21	836%
(6)	Data fixed (public node)	GB	375	374	-0.27%
(7)	Public node yearly $[(4) + (6)]$	GB	427	861	102%
(8)	Private node yearly $[(5)]$	GB	2.21	21	836%
(9)	Average node $[(7) \times \frac{1.35}{2.11} + (8) \times \frac{0.76}{2.11}]$	GB	274	558	104%

Table 14: Network traffic generated by the average node

IP network electrical intensity

The electrical intensity of the internet protocol (IP) network used in the model is based on a value from the IEA (International Energy Agency)[1]. In the article the range of intensity in kWh per GB is between 0.023 and 0.25. The value considered in the present study is the average 0.128 kWh / GB, a sensitivity analysis of this parameter is conducted in section §4.3.1. Electrical consumption of data exchange over the internet has been modelled using baker's average country mix.

3.2.3. Electricity generation models

The impact related to electricity consumption is considered to be location-based, i.e. based on the average electricity mix of a given country/region. Information concerning the use of renewable electricity and special contracts is not complete enough to be taken into account.

The modules from Ecoinvent 3.8 were used to model electricity consumption. The shares of electricity technologies are valid for the year 2018. The shares have been calculated based on statistics from 2018: IEA World Energy Statistics and Balances. OECD iLibrary, eISSN:1683-4240, DOI: 10.1787/enestats-data-en and ENTSO-E: Physical Energy & Power Flows, Grid losses are based on data from 2018 (also IEA World Energy Statistics and Balances).

Influence of the electricity model on the results is presented as a sensitivity analysis (cf. 4.3.1).

[1] George Kamiya. « The Carbon Footprint of Streaming Video: Fact-Checking the Headlines – Analysis ». IEA. https://www.iea.org/commentaries/the-carbon-footprint-of-streaming-video-fact-checking-the-headlines.

3.2.4. Transport models

In the system considered for the LCA study, the transport phases considered are the transport of IT devices used by bakers or in datacenters to its use location, and the transport of the equipment to its end-of-life treatment. The generic modules used to describe the transport are listed in Appendix B. Raw materials transport are included in their generic modules from the Ecoinvent database.

Generic distances were used to describe transport. The distances are based on an ADEME report[1] and are listed in the table below. Half of the equipment is assumed to be transported by boat and half by air. A sensitivity analysis of this parameter is conducted in section §4.3.7.

	Boat	Plane	Road
Air transport (km)	0	9,000	1,300
Boat transport (km)	18,000	0	1,800

Table 15: Transport distances

In the end-of-life of equipment a generic distance of 50 km to the treatment plant was considered.

3.2.5. End of life modelling

The end-of-life was modelled using a cut-off approach. For recovered matter and recycled elements, only the impact of the treatment is considered without any avoided impact.

As explained in §2.3.2.2, the end of life of packaging is not included in the study. In addition, for IT equipment modelled using Ecoinvent modules (computer, laptop), the end of life is included in the equipment module and was not modified.

Finally, for IT equipment that were modelled for the study, treatment for recycling of 40% of the IT equipment was considered based on recycling figures in Europe (42%)[2] and the US (40%)[3]. For the recycled equipment, the PWB and aluminum treatment in preparation for the recycling is modelled and the plastic is incinerated. Ecoinvent modules used for the end of life are presented in Appendix B.2.

The equipment that is not recycled is considered to be landfilled. However, as presented in §2.3.2.2, landfilling of IT equipment is not considered in the study.

3.3. Modelling and lifecycle inventory calculation tool

To model the systems and calculate the LCA inventories and environmental impacts, the TEAM™ software, version 5.4 was used. TEAM™ is PwC's tool for LCA. TEAM™ allows the user to build up and manage large databases and model any system representing the different industrial operations relative to the products, processes and activities of a company. Impacts of production of all inputs (ex. 1 kg of cardboard or 1 kWh of electricity) are modelled thanks to databases (Ecoinvent 3.8 cut-off models or PwC's database). Most elements are modelled using variables to facilitate sensitivity analyses.

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1 LHOTELLIER, Johan, Etienne LESS, Emilie BOSSANNE, Sandrine PESNEL, ADEME, et RDC ENVIRONMENT. 2018. « Modélisation et évaluation du poids carbone de produits de consommation et biens d'équipement ». ADEME. https://librairie.ademe.fr/consommer-autrement/1190-modelisation-et-evaluation-du-poids-carbone-de-produits-de-consommation-et-biens-d-equipement.html.

2 « Statistics | Eurostat ». https://ec.europa.eu/eurostat/databrowser/view/T2020_RT130/bookmark/table?lang=en&bookmarkId=a69be825-957e-473c-a81f-f02866dc9141.

3 Schumacher, Kelsea A. 2016. « Electronic waste management in the U.S.: practice and policy ». Thesis, University of Delaware. https://udspace.udel.edu/handle/19716/20333.

4. SECTION IV – Results

4.1. Limits of the LCA study

This study has potential limitations relating to the scope studied, data collection and existing life cycle inventories in databases.

- Scope of the study
    - The study considers the impact of Tezos core protocol, and there are many applications built around the protocol which are not included in this study. For instance, the impact of end users initiating transactions or using the smart contract is not included. Therefore, as discussed in this study, the impact per service (transaction or gas quantity) of the blockchain core protocol appears to decrease with wider adoption, but there might be rebound effects due, for instance, to the development of new applications, websites or increased use of wallets.
    - The study considers nodes of bakers, due to limitation in data availability for other nodes like chain explorers, wallets and other type of services that need access to the blockchain history. One measure performed in May 2021 by the Company estimated total public nodes to be 68% higher compared to public baker nodes.
    - The end-of-life of equipment was modelled using a simplified methodology.
- Data collection
    - A large portion of the hypotheses are built on a sample of bakers addressed through a questionnaire. This sample of 70 respondents is believed to be representative of the population, but a bias might exist in the diffusion method of the questionnaire, or the typology of baker susceptible to answer this questionnaire. The average number of active bakers in 2021 at the time of this study was 411 (from January until mid-November).
    - The location of bakers' nodes is derived from the location of all the public nodes on the blockchain with the hypothesis that the distribution is similar.
    - The Company is not directly responsible for the equipment generating impact, therefore direct access to data was limited. Some data were made available by bakers during the interviews, notably on their baking set-up and data exchanges.
    - The data collected regarding internet traffic showed a correlation between blockchain activity and the quantity of data exchange. However, the uncertainty on the equation correlating the number of transactions and network exchanges remains high.
- Life cycle inventories databases
    - Most of the equipment described in this study are state-of-the-art technology. Therefore, the precise impact associated with their production remains little known. The supposed best data available and the soundest possible hypotheses were used, but the results of the model for the embodied impacts of some equipment or system, such as SSD disk and cloud computing, still contain uncertainties.

PwC has not audited or verified the information provided to them within the scope of the work, regardless of its source.

PwC cannot guarantee that PwC got to know all relevant documentation or information that may be in existence and therefore cannot comment on the completeness of the documentation or information made available to PwC. Any documentation or information brought to PwC attention subsequent to the date of this study may require PwC to adjust and qualify this study accordingly.

In addition, environmental impact evaluations carry uncertainty. The following table gives the uncertainty range of the considered indicators[1].

Indicator	Uncertainty
Total primary energy	20%
Total electricity	20%
Resource use, minerals and metals	20%
Resource use, fossil fuels	20%
Greenhouse effect	20%
Particulate matter	30%

Table 16: Uncertainty on impact results

[1] Uncertainties discussed during a study group at the AFNOR.

4.2. Results (reference scenario)

4.2.1. Results for one node

The following table presents results for the average baker's node running for one year.

Results interpretation:

- **Core development** represents the electricity consumed by the developers' laptop
- **Baking equipment – embodied** represents the environmental impact associated with the raw material extraction, production, transport and end-of-life of the device running the node and the security equipment.
- **Baking equipment – Use** corresponds to the electricity consumed by the devices running and securing the node.
- **Internet access equipment – Embodied** is the environmental impact associated with the raw material extraction, production, transport and end-of-life of internet access equipment (router at baker home and network equipment in datacenters).
- **Internet access equipment – Use** corresponds to the electricity consumed by the internet access equipment.
- **Internet protocol network** represents the environmental impact associated with the use of the IP core network, meaning the electrical consumption associated with the exchange of data over the internet.

These results reflect the potential impact of an average node over the 2021 year.

Impact	Unit	One node	Core develop-ment	Baking equipment - Embodied	Baking Equipment - Use	Internet access equipment - Embodied	Internet access equipment - Use	Internet Protocol network
Greenhouse effect	kg CO_2 eq.	161	1.64%	8.52%	49.51%	8.24%	12.02%	20.07%
Resource use, fossils	MJ	3,132	1.78%	6.35%	51.92%	6.29%	12.61%	21.05%
Resource use, minerals and metals	g Sb eq.	8.66	0.39%	34.46%	7.24%	53.21%	1.76%	2.94%
Particulate Matter	Disease Incidence	3.82E-05	0.98%	10.22%	47.55%	10.42%	11.55%	19.27%
Total primary energy	MJ	3,324	2.01%	6.53%	51.58%	6.45%	12.53%	20.91%
Total electricity	MJ	1,151	2.25%	0.03%	59.28%	0.01%	14.40%	24.03%

Table 17: Impact results for the average 2021 node

The baking equipment (including the security equipment) is the primary source of potential environmental impact for five out of the six indicators considered (the one exception being the use of minerals and metals), mainly through its use phase. For instance, around 60% of CO_2e emissions originate from the baking equipment. 85% of these are linked to the electrical consumption during the use phase and 15% to the embodied emissions from the raw material acquisition, manufacturing, transport, packaging and end-of-life.

The two main contributors to the use of minerals and metals are the internet equipment (55%) and the baking equipment (41%). 89% of this potential impact is linked to the embodied impact of these pieces of equipment.

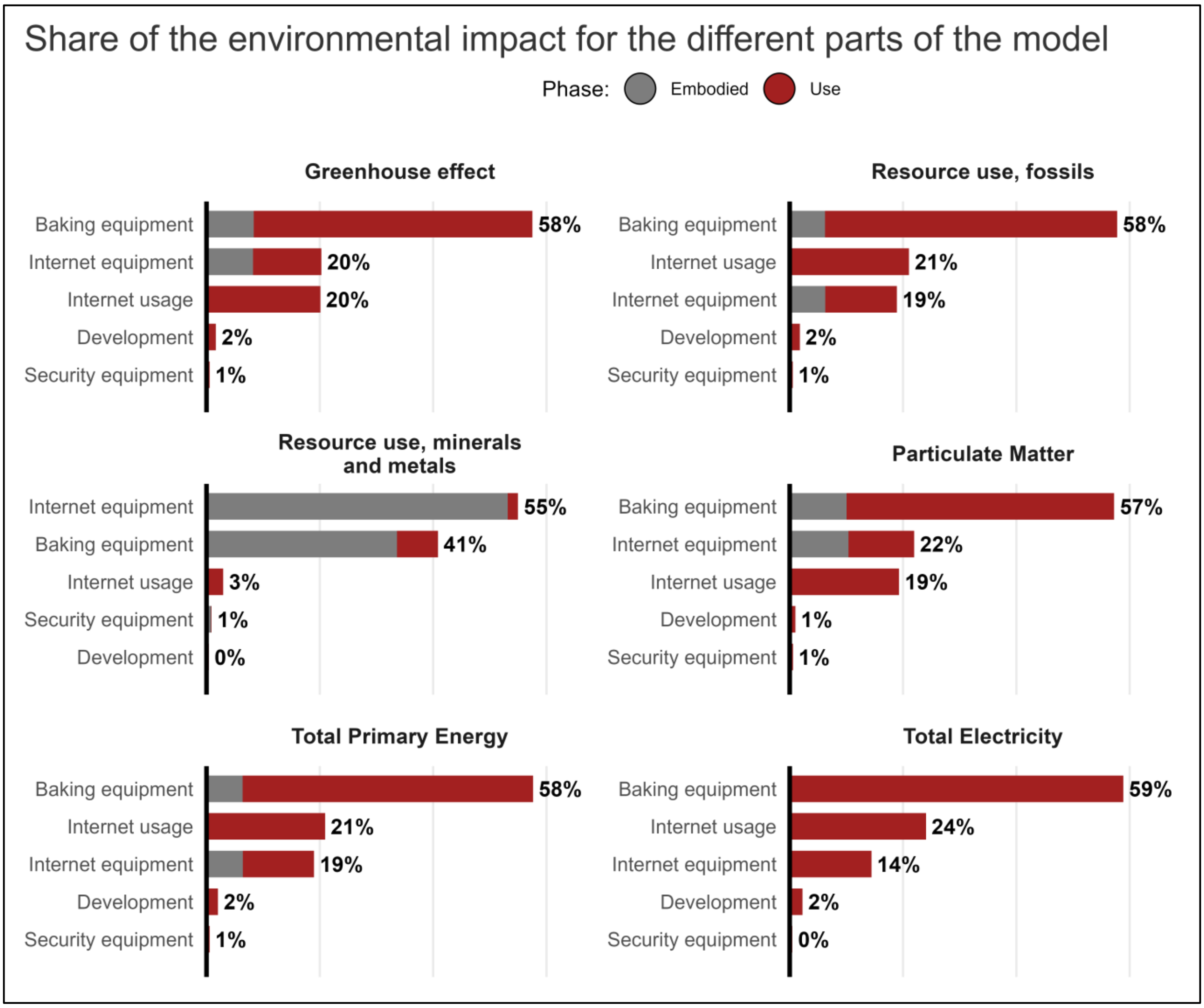

Figure 8: Environmental impact by indicator

(Security equipment were included with the baking equipment in Table 17)

4.2.2. Results for the blockchain protocol

The following parameters are considered for each period:

	2020	2021 Before Granada	2021 After Granada[1]	2021	Trend 2020 2021	Source
Transactions	6,066,719	18,228,211	38,548,406	56,776,617	836%	TzStats
Gas[2]	6.69E+10	4.23E+11	2.40E+11			TzStats
Number of bakers	445	417	394	411	-8%	TzStats
Number of nodes per baker[3]	2.11	2.11	2.11	2.11	-	Questionnaire

Table 18: Key defining parameters of the blockchain in 2020 and 2021

The total value for the blockchain is calculated by multiplying the value for one node with the number of bakers and the number of nodes per baker.

Impact	Unit	For the blockchain protocol (all baker nodes)		For one transaction		For one gas unit
		2020	2021	2020	2021	2021 – After Granada
Greenhouse effect	kg CO_2 eq.	135,950	139,711	2.24E-02	2.46E-03	2.44E-07
Resource use, fossils	MJ	2,628,324	2,716,489	4.33E-01	4.78E-02	4.76E-06
Resource use, minerals and metals	g Sb eq.	8,025	7,506	1.32E-03	1.32E-04	1.23E-08
Particulate matter	Disease incidence	3.24E-02	3.31E-02	5.33E-09	5.83E-10	5.76E-14
Total primary energy	MJ	2,790,649	2,882,545	4.60E-01	5.08E-02	5.05E-06
Total electricity	MJ	948,612	997,886	1.56E-01	1.76E-02	1.77E-06

Table 19: Environmental impact for all baker nodes, for one transaction and for one gas unit

With a similar number of bakers and a larger service offer, the impact of the blockchain for each transaction is lowering (see Figure 9). Indeed, the energy consumption by the consensus protocol of Tezos is not increasing proportionally with the increase in the number of transactions. The total blockchain protocol potential impacts increased by between 2% to 5%, except for the resource use of mineral and metals that decreased by 6% due to the decrease in the number of bakers. At the same time, the number of transactions increased by 836%.

However, as explained in the limits to the study (cf. §4.1), increased adoption of the blockchain may create rebound effect on the environmental impacts of the Tezos ecosystem as a whole: the impact of the core protocol

[1] The transactions realized and gas consumed between November the 16th and the end of the year were extrapolated using the transactions and gas use rate between the Granada update (August 6th) and November the 15th.
[2] The quantity of gas is not comparable between 2020 and 2021 due to the change in the value of a gas unit following the Granada amendment.
[3] Only nodes operated by bakers are considered for these results.

per transaction lowers but the widening and the intensification of the usage of the Tezos ecosystem with new applications and more users could increase the total environmental impact.

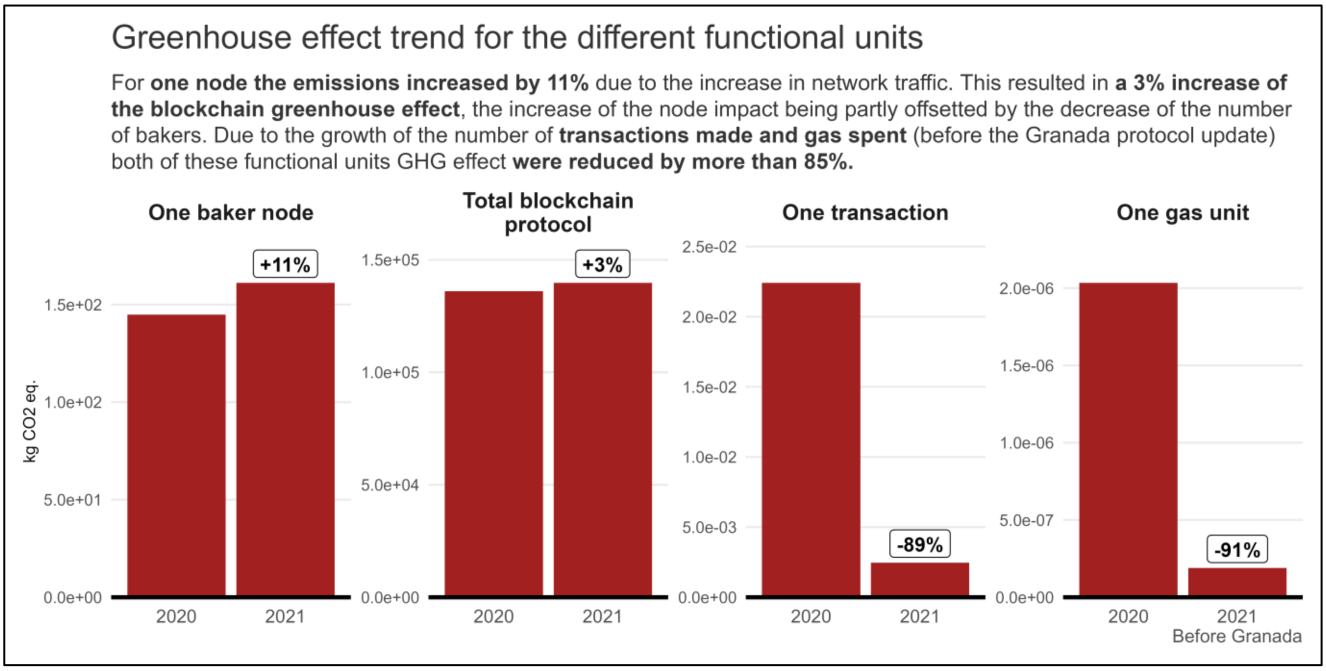

Figure 9: Trend of potential greenhouse effect between 2020 and 2021

Under the default scenario, the greenhouse effect increases by 3% for the blockchain protocol between 2020 and 2021 due to the change in activity. In the sensitivity analyses, alternative hypotheses on the internet protocol network electrical intensity (4.3.3) and the quantity of data exchanged by the nodes (4.3.4) were tested. When taking into account the most conservative approaches in these sensitivity analyses, the model becomes more sensitive to the number of transactions. With the high electrical intensity of the internet network hypothesis, the blockchain protocol greenhouse effect impact increases by 10%, and when considering the upper bond of the data exchange hypothesis, it increases by 12%. The detailed results of the sensitive analyses for all the potential impacts can be seen in Tables 21 and 24.

4.2.3. Carbon footprint performance for running one node on different devices

The studied system includes several alternative equipment. It is interesting not only to look at the average performance, but also how the different equipment performs environmentally.

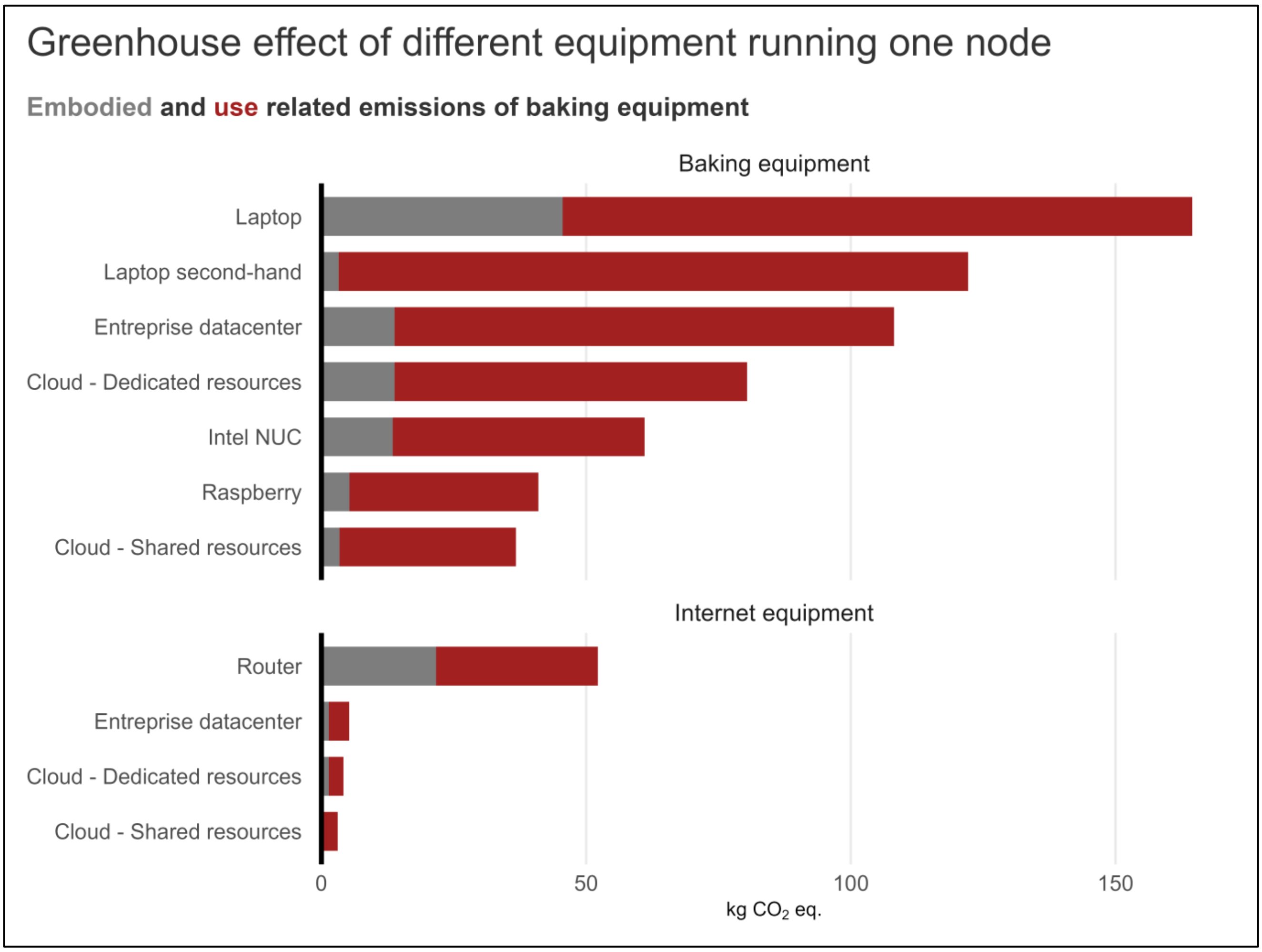

Figure 10: Greenhouse effect of different equipment running one node

This figure illustrates the weight of the embodied greenhouse effect in the total greenhouse effect for an equipment. It illustrates the benefit of using second-hand computers, as running one node for a year with a second-hand computer generates 26% less GHG emissions compared to using a new laptop.

Although using a second-hand computer reduces embodied emissions, most emissions are generated during the use phase. As a result, the most effective equipment for personal bakers are low consuming single-board devices. The Raspberry Pi generates 75% less GHG emissions compared to the laptop and the Intel NUC 63% less.

This figure also illustrates the benefits of using shared resources instances in the cloud instead of dedicated resources. It can significantly lower GHG emissions (almost halving it in the model of this study). However, according to the interviews, it is at the cost of a reduced reliability.

Finally, in the model, the internet equipment in data center and cloud is having a lower contribution to the environmental impacts compared to personal baker equipment. This is because the amount of internet access equipment per server in a data center is rationalized, whereas the model considers 77% of one router for a node at a baker's home.

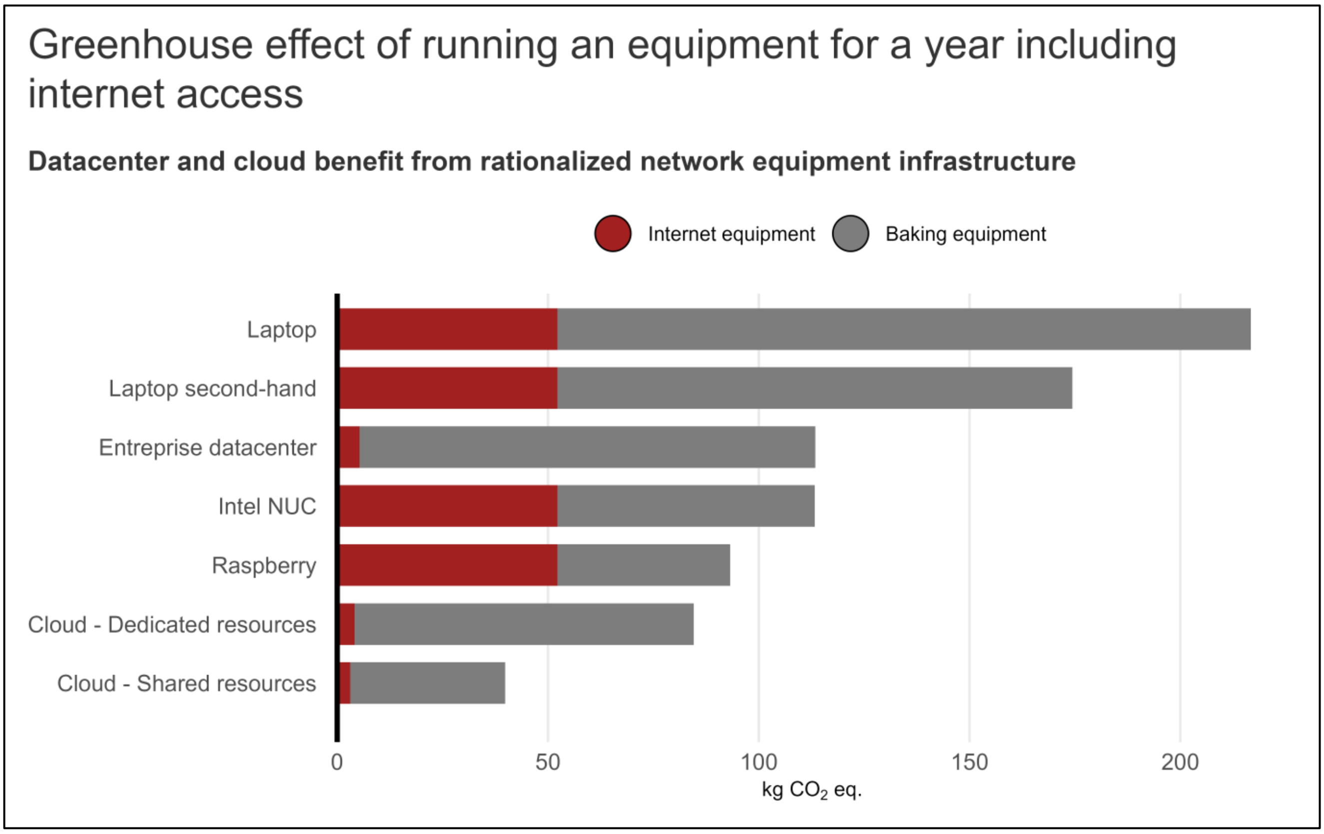

Figure 11: Greenhouse effect of running an equipment for a year including internet access

Figure 1111 includes the embodied and use phase greenhouse effect of the internet access equipment and the equipment running the node. In the system, the internet access equipment represents between 24% and 56% of GHG emissions of a baker running a node from its home and only 4% to 8% for a node running in a data center.

As explained in 3.2.2.2, the router of a baker running the node from home is allocated at 77% to the baking based on a time-of-use estimation. In the sensitivity analyses, the consequences of allocating the router to the baking at 50% or 0% are explored (cf. §4.3.2).

4.3. Sensitivity analyses

As a reminder, the following analyses are performed on the scope of the study, which is the network of bakers' nodes. For some of the analyses, the abiotic depletion potential of elements is not presented when the tested parameter affects only the usage of the equipment and not the embodied footprint. Unless specified, all the sensitivity analyses are performed using the data of 2021.

4.3.1. Test of model sensitivity to the electrical mix

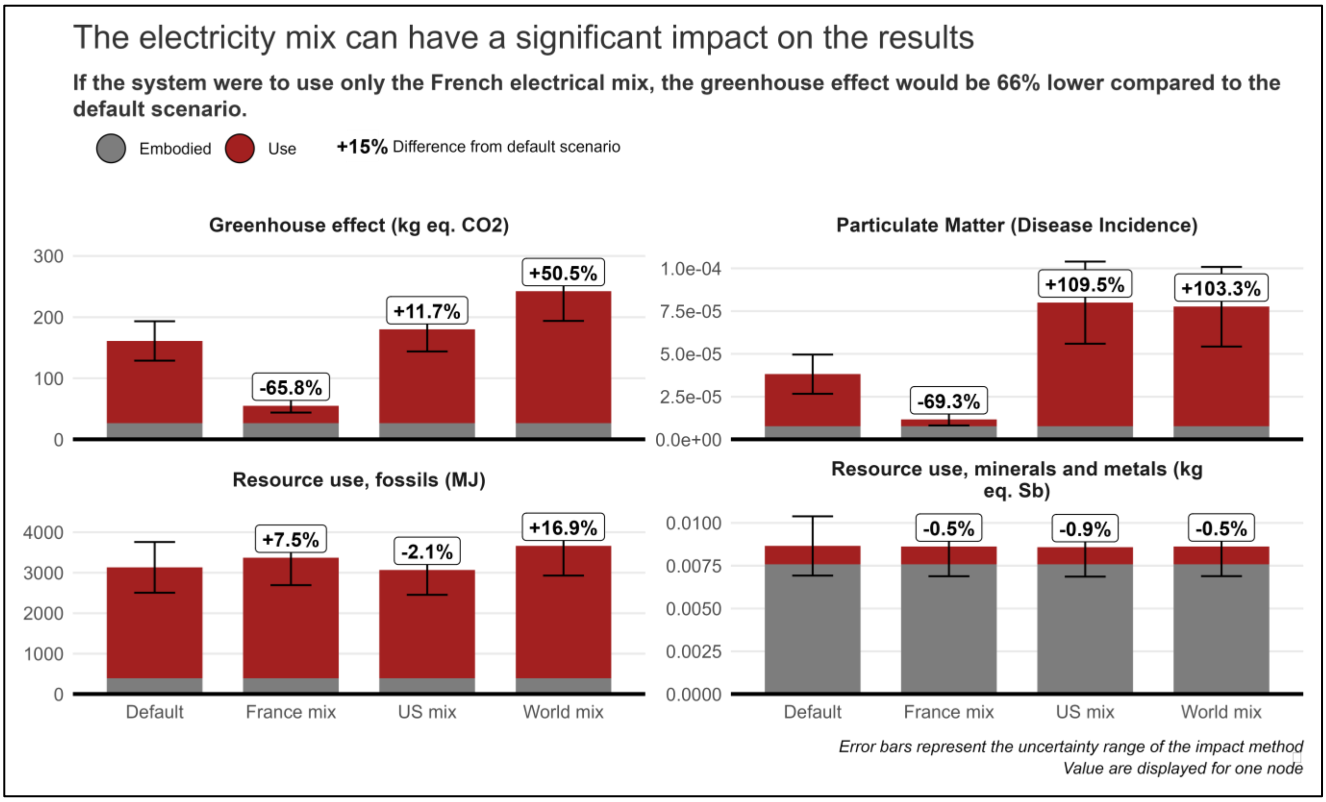

Figure 12: Model sensitivity to electricity mix

The model is very sensitive to the electrical mix powering the bakers' equipment and the internet network. A sensitivity analysis was performed considering the electricity mix of two countries where bakers are present, with a lower carbon intensity such as France and a higher carbon intensity such as the US. An average world mix was also studied. The mix of the bakers is based upon the IP addresses gathered by the cartographer node when exploring the network and is presented in Table 12. If the electrical mix of bakers' countries was replaced by the French mix, greenhouse gas emissions could be 66% lower. On the other hand, considering that all the electricity consumption was from a US or a world average mix would increase greenhouse gas emissions by 11% and 50% respectively.

4.3.2. Test of model sensitivity to router allocation hypothesis

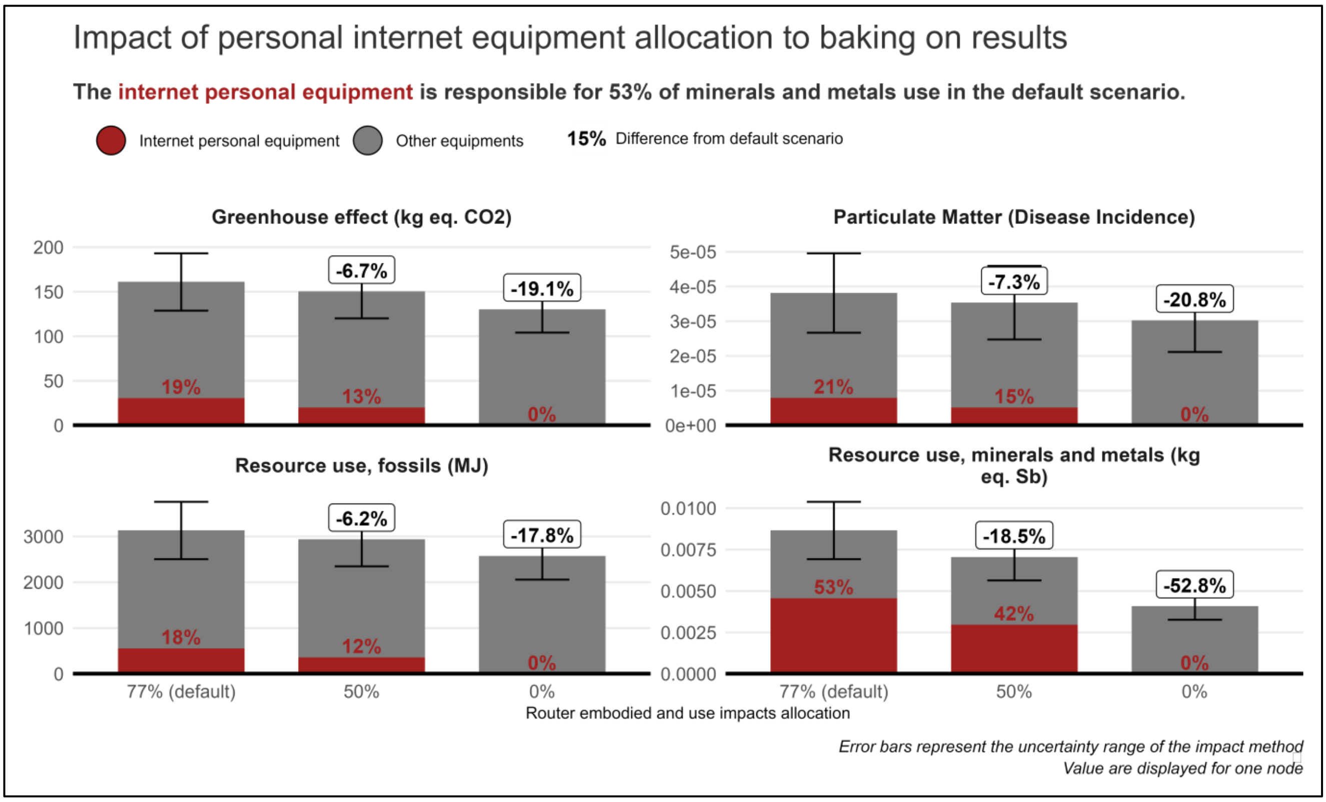

Figure 13: Test of model sensitivity to router allocation hypothesis

As explained in section 3.2.2.2, the router of a baker running the node from home is allocated at 77% to the baking activity based on a time-of-use estimation. This is a conservative approach; however, another approach would be to consider that bakers would have had a router at home, running all year long even if they were not baking. This graph illustrates the impact on the total results with different allocation hypotheses, attributing the router to the baking at 50% would reduce greenhouse gas emission by 7%, and not considering the router in the system would reduce greenhouse gas emission by 19%.

4.3.3. Test of model sensitivity to Internet Protocol network electrical intensity

As explained in section 3.2.2.5, the model considers the average electrical intensity for internet exchanges in the range given by the IEA. In the sensitivity analysis, the minimal and maximum values are tested, the maximum value being around nine times as much as the minimal value.

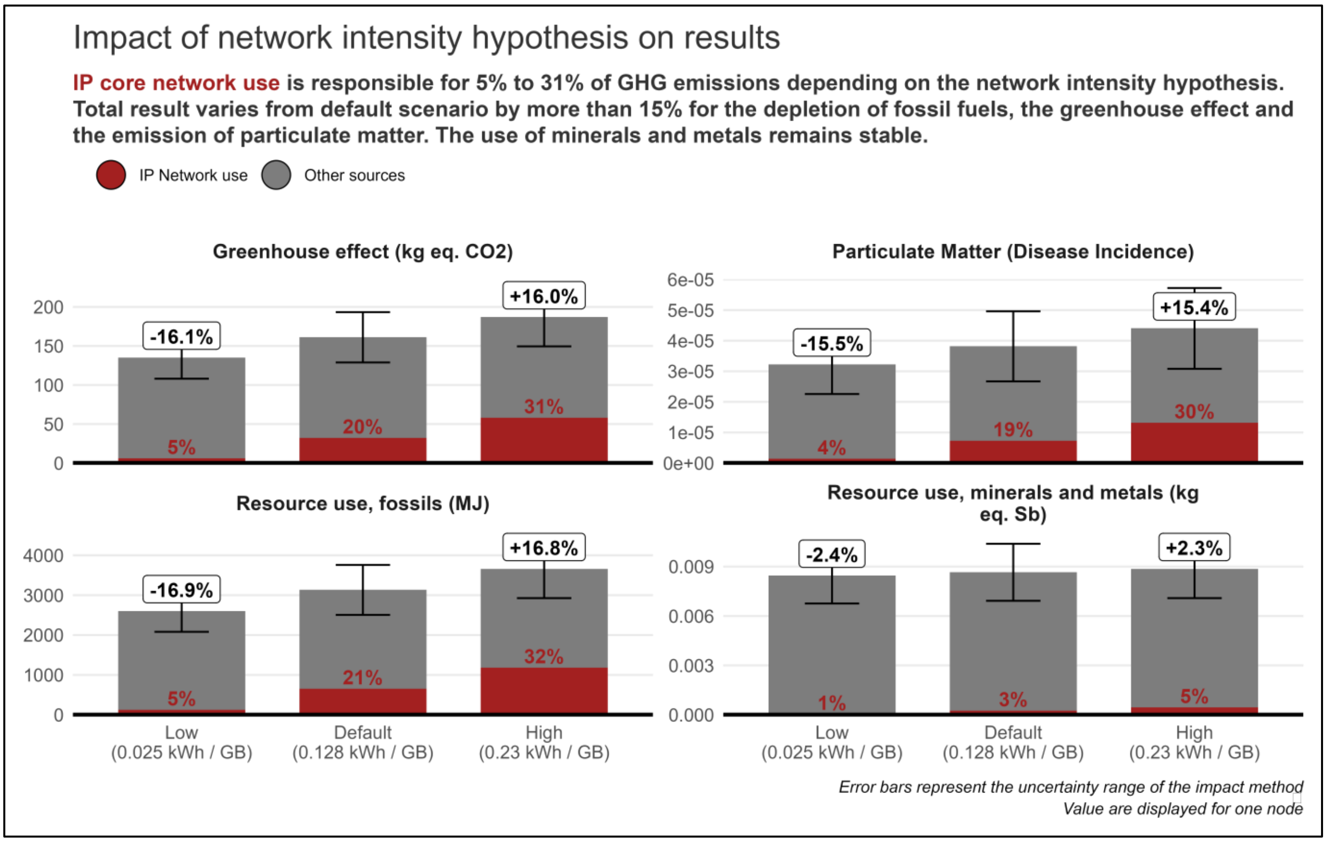

Figure 14: Test of model sensitivity to IP network electrical intensity hypothesis

The model is sensitive to the network electrical intensity hypothesis, with impact indicators varying by 30% between minimum intensity and maximum intensity. The upper bond of this intensity (respectively the lower bond) would lead to an increase in greenhouse effect (respectively a decrease) of 16%. Similarly, the fossil fuel depletion potential would increase (respectively decrease) by 17%, and the emission of particulate matter by 15%.

This sensitivity analysis was also run for the results in 2020. The following table presents the results for one node in 2020 under the different hypotheses.

Indicator	Unit	Low (0.025 kWh / GB)	Default (0.128 kWh / GB)	High (0.23 kWh / GB)
Greenhouse effect	kg CO_2 eq.	132	145	157
Particulate Matter	Disease Incidence	3.15E-05	3.45E-05	3.73E-05
Resource use, fossils	MJ	2,536	2,799	3,054
Resource use, minerals and metals	kg Sb eq.	8.44E-03	8.45E-03	8.64E-03

Table 20: Results for one node in 2020 under the different IP network intensity hypotheses

The goal of performing this sensitivity analysis on the 2020 period is to see the influence of this assumption on the impact trends between 2020 and 2021. The following table summarizes the trend for the different functional units under the three scenarios for the internet protocol network electrical intensity.

Trend 2020 to 2021 for the different network intensity hypotheses				
		Low intensity (0.025 kWh / GB)	**Default (0.128 kWh / GB)**	**High intensity (0.23 kWh / GB)**
For one baker node	Greenhouse effect	4%	11%	21%
	Particulate Matter	4%	11%	20%
	Resource use, fossils	5%	12%	23%
	Resource use, minerals and metals	0%	1%	3%
For the protocol (all baker nodes)	Greenhouse effect	-4%	3%	12%
	Particulate Matter	-4%	2%	11%
	Resource use, fossils	-3%	3%	13%
	Resource use, minerals and metals	-7%	-6%	-5%
For one transaction	Greenhouse effect	-90%	-89%	-88%
	Particulate Matter	-90%	-89%	-88%
	Resource use, fossils	-90%	-89%	-88%
	Resource use, minerals and metals	-90%	-90%	-90%

Table 21: Trend of the results between 2020 and 2021 under different IP network electrical intensity scenarios

With the high electrical intensity of the internet network hypothesis, the model is more sensitive to the number of transactions. Therefore, the blockchain protocol greenhouse effect impact would increase between 2020 and 2021 by 10% in this scenario, compared to only 3% in the default scenario.

4.3.4. Test of model sensitivity to the quantity of data exchanges over the Internet

As explained in section 3.2.2.5, the reference model considers that the exchanged data quantity over the internet can be calculated from the number of transactions with an affine function. This relation was determined using a simple average from the data collected from a few bakers.

In the sensitivity analysis, the lower bound is defined as the minimum value observed for both the fixed and variable parts for one node and the upper bond as the maximum value observed for both parts.

	Public node (GB)	Private node (GB)	Average node (GB)
Lower bound	389	21	256
Default	861	21	558
Upper bound	1,519	21	979

Table 22: Network traffic sensitivity analyses lower and upper bond in GB per year (2021)

The private node data traffic does not evolve because only one source was available during the data collection. In addition, its impact on the volume of data exchanged is minimal.

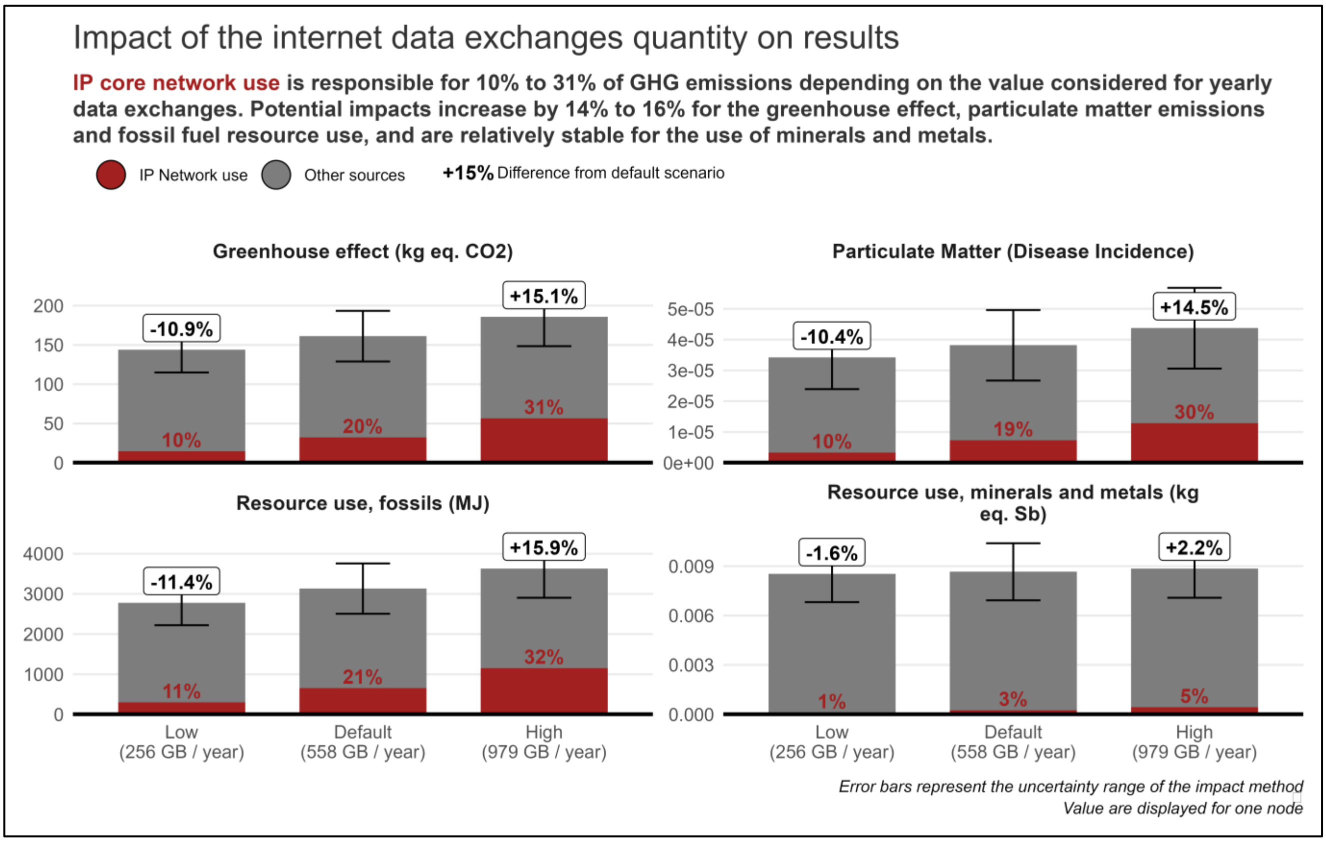

Figure 15: Test of model sensitivity to IP network data exchanges yearly rates

An increase of 75% of data exchanged by the average node would increase its fossil fuel depletion potential by 16%, its greenhouse effect by 15%, and the particulate matter emissions would increase by 15%.

This sensitivity analysis was also performed for the year 2020.

	Public node (GB)	Private node (GB)	Average node (GB)
Lower bound	231	2	149
Default	427	2	274
Upper bound	643	2	412

Table 23: Network traffic sensitivity analyses lower and upper bond in GB per year (2020)

The following table shows the trend of the functional units between 2020 and 2021 when comparing the results with the lower bound and higher bound hypotheses.

Trend 2020 to 2021 for the different data exchanges scenarios				
		Lower bound scenario	**Default scenario**	**Higher bound scenario**
For one baker node	Greenhouse effect	2%	11%	19%
	Particulate Matter	2%	11%	18%
	Resource use, fossils	2%	12%	20%
	Resource use, minerals and metals	0%	1%	2%
For the protocol (all baker nodes)	Greenhouse effect	-5%	3%	10%
	Particulate Matter	-6%	2%	9%
	Resource use, fossils	-5%	3%	11%
	Resource use, minerals and metals	-8%	-6%	-5%
For one transaction	Greenhouse effect	-90%	-89%	-88%
	Particulate Matter	-90%	-89%	-88%
	Resource use, fossils	-90%	-89%	-88%
	Resource use, minerals and metals	-90%	-90%	-90%

Table 24: Network traffic sensitivity, trend 2020 to 2021

When considering the upper bond of the data exchange hypothesis, the model is more sensitive to the number of transactions. Therefore, the blockchain protocol greenhouse effect impact would increase between 2020 and 2021 by 12% in the higher bound scenario, compared to only 3% in the default scenario.

4.3.5. Test of model sensitivity to the share of public nodes

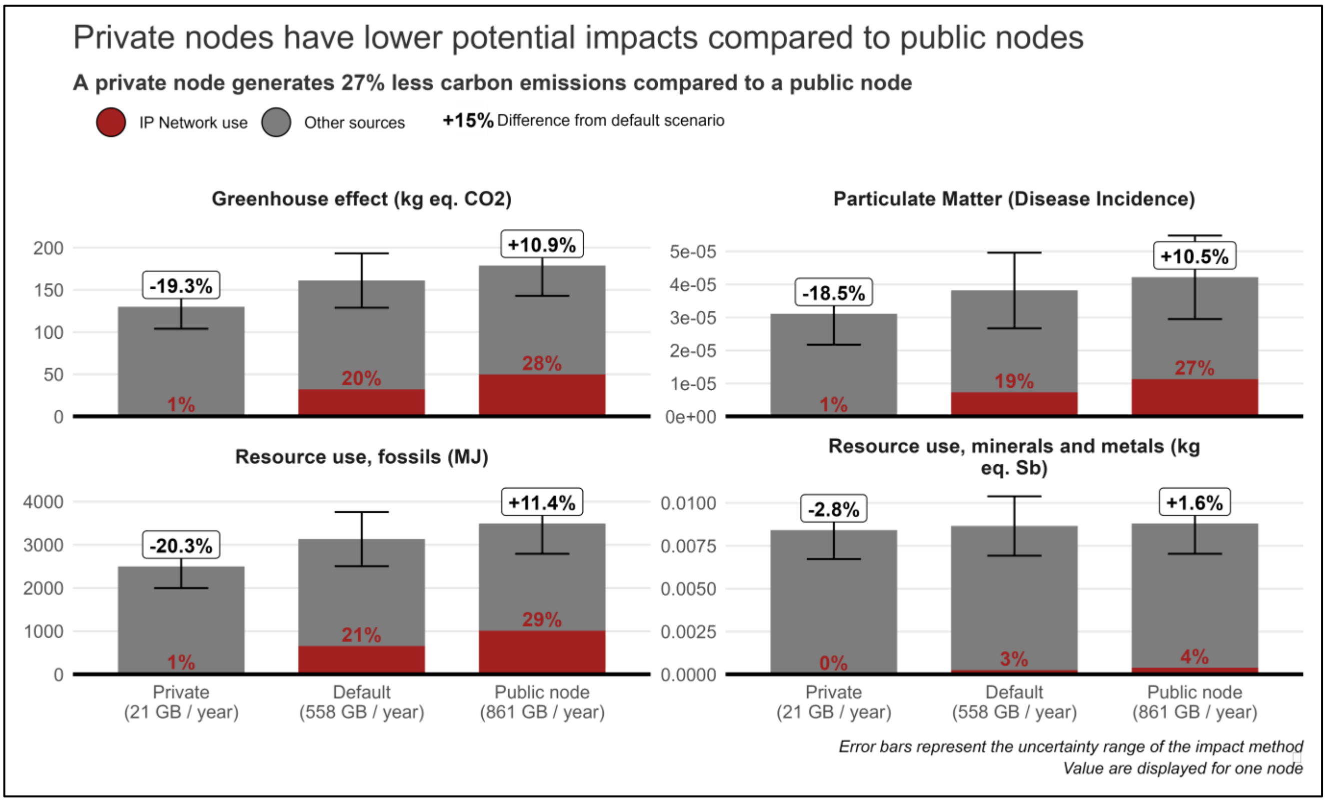

Figure 16: Compared environmental impact of private and public nodes

The model is sensitive to the share of private and public nodes. In the default scenario, 64% of nodes are public nodes. Private nodes are generating a lesser impact compared to public nodes because they are generating fewer data exchanges over the internet (21 GB per year vs 861 GB per year, 98% less). The range of reduction in impact between a public and a private node for the first three environmental indicators in Figure 16 is from 26% to 28%. The mineral and metal resources use is stable between a public and private node because the two nodes are using the same equipment (the equipment embodied impact is responsible for 96% of this impact).

4.3.6. Test of model sensitivity to the Power Usage Effectiveness (PUE) hypothesis

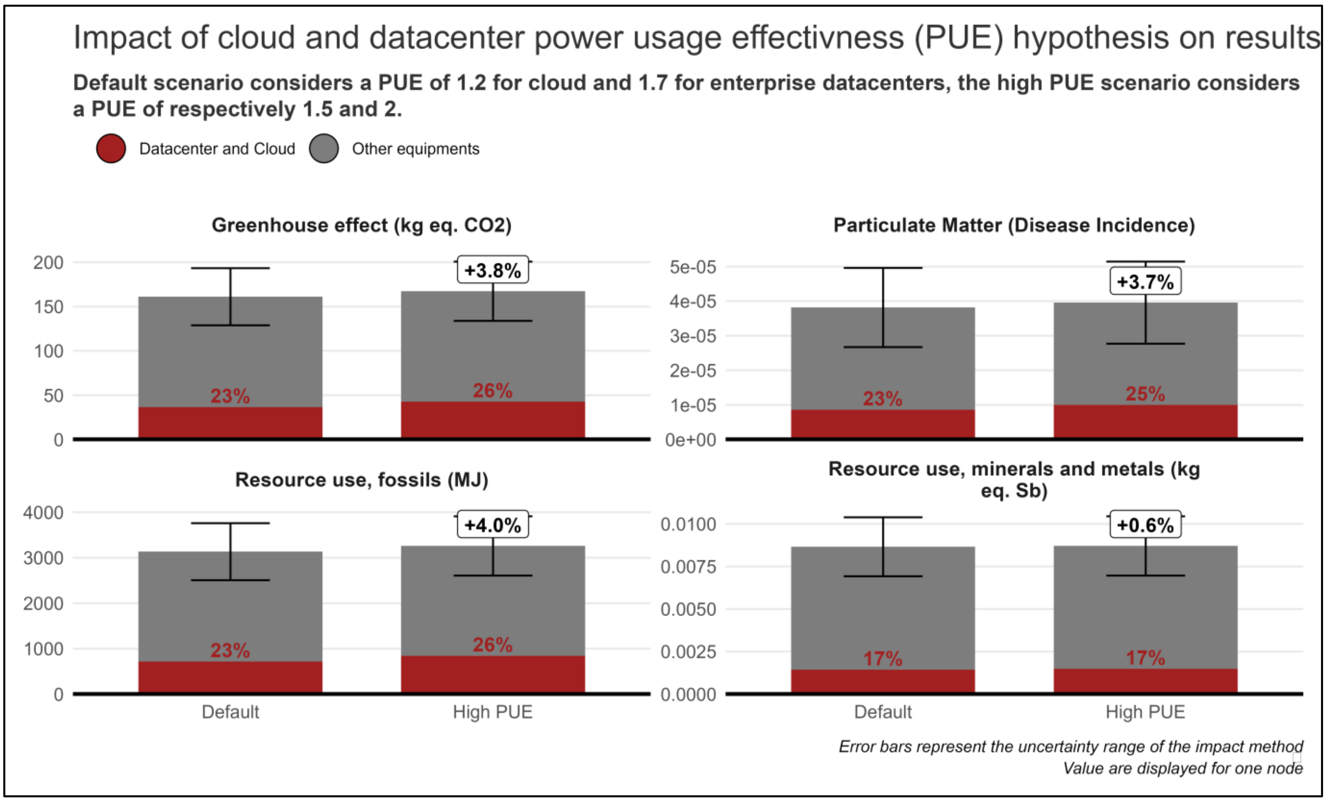

Figure 17: Test of model sensitivity to the PUE hypothesis

The model is not sharply sensitive to the PUE hypothesis, because only 41% of bakers use data centers or cloud services and tend to have less impact compared to personal baking equipment (except single board computers).

4.3.7. Test of model sensitivity to the transport hypotheses

The transport hypotheses are described in 3.2.4, and consider that half of the equipment is transported by boat and half by plane. The sensitivity test shows no significant difference if the model would consider all equipment transported either by air or boat as shown in the following table.

Impact	Unit	100% Air transport	Node in default scenario	100% Sea transport
Greenhouse effect	kg eq. CO_2	1%	161	-1%
Particulate Matter	Disease Incidence	0%	3.82E-05	0%
Resource use, fossils	MJ	1%	3,132	-1%
Resource use, minerals and metals	kg Sb eq.	0%	8.66E-03	0%

Table 25: Test of model sensitivity to the transport hypotheses

4.3.8. Sensitivity analyses summary

The table below summarizes the results of the sensitivity analyses across the 4 impact indicators and two energy indicators. The results for which the difference with the reference scenario is superior to the indicator uncertainty, are highlighted.

Indicator	Greenhouse effect	Particulate Matter	Resource use, fossils	Resource use, minerals and metals	Total Electricity	Total Primary Energy
Units	kg CO_2 eq.	Disease Incidence	MJ	kg Sb eq.	MJ	MJ
Uncertainty	20%	20%	20%	30%	20%	20%
Reference scenario	**161**	**3.82E-05**	**3,132**	**8.66E-03**	**1,151**	**3,324**
100% Air transport	1%	0%	1%	0%	0%	1%
100% Sea transport	-1%	0%	-1%	0%	0%	-1%
France mix	-66%	-69%	7%	-1%	3%	11%
US mix	12%	110%	-2%	-1%	-1%	2%
World mix	50%	103%	17%	0%	2%	22%
Router - 0% allocation	-19%	-21%	-18%	-53%	-13%	-18%
Router - 50% allocation	-7%	-7%	-6%	-19%	-5%	-6%
High PUE	4%	4%	4%	1%	5%	4%
Private node	-19%	-19%	-20%	-3%	-23%	-20%
Public node	11%	10%	11%	2%	13%	11%
Network - Low intensity (0.025 kWh/GB)	-16%	-16%	-17%	-2%	-19%	-17%
Network - High intensity (0.23 kWh/GB)	16%	15%	17%	2%	19%	17%
Data exchanges - Lower bound (256 GB / year)	-11%	-10%	-11%	-2%	-13%	-11%
Data exchanges - Upper bound (979 GB / year)	15%	15%	16%	2%	18%	16%

Table 26: Sensitivity analyses summary in 2021

Indicator	Greenhouse effect	Particulate Matter	Resource use, fossils	Resource use, minerals and metals	Total Electricity	Total Primary Energy
Units	kg CO_2 eq.	Disease Incidence	MJ	kg Sb eq.	MJ	MJ
Uncertainty	20%	20%	20%	30%	20%	20%
Reference scenario	**145**	**3.45E-05**	**2,799**	**8.55E-03**	**1,010**	**2,972**
Network - Low intensity (0.025 kWh/GB)	-9%	-8%	-9%	-1%	-11%	-9%
Network - High intensity (0.23 kWh/GB)	9%	8%	9%	1%	11%	9%
Data exchanges - Lower bound (149 GB / year)	-5%	-5%	-5%	-1%	-6%	-5%
Data exchanges - Upper bound (412 GB / year)	6%	5%	6%	1%	7%	6%

Table 27: Sensitivity analyses summary in 2020

5. Section V - Summary

Nomadic Labs (the "Company'"), French subsidiary of Tezos Foundation, has commissioned PricewaterhouseCoopers Advisory SAS - a French member firm of the PwC network of member firms, each of which is a separate legal entity - (hereinafter "PwC") to perform a study to analyze the environmental footprint of Tezos, a public permissionless blockchain, based on a proof-of-stake protocol. This study has been prepared only for the Company and solely for the purpose agreed with PwC. PwC accepts no liability to anyone else than the Company or for any other purpose in connection with this study.

The present report aims at analyzing these impacts through a **LCA approach**, in accordance with the requirements of ISO 14040 and 14044 standards.

The study is focusing on the three following **functional units** related to Tezos blockchain:

- Running a node as a baker
- Making one transaction
- Consuming one gas unit for a smart contract

The **system boundaries** include the core protocol development; embodied (production, packaging, transport, end-of-life) and use impact of bakers' equipment to connect to the network and sign transactions; electricity consumption of Internet usage.

The calendar **year 2020 and the period January to mid-November 2021 extrapolated** to one year were studied to consider the increase of the Tezos adoption in 2021.

The analysis is based on **data collected from a panel of bakers from mid-March to end-April 2021**, from Tezos explorers, bibliographic literature and recognized LCA databases.

The following indicative results consider only the bakers' nodes and must be considered together with the data, hypotheses and limitations detailed in this report. As an example, in 2021, **running one node for a year as a baker represents around 161 kg CO_2 eq., making one transaction on the blockchain 2.46 g CO_2 eq. and consuming one gas unit for a smart contract 2.44E-4 g CO_2 eq.**

Indicator	Unit	For the blockchain protocol		For one node		For one transaction		For one gas unit
		2020	2021	2020	2021	2020	2021	2021 (AG[1])
Greenhouse effect	kg CO_2 eq.	135,950	139,711	145	161	2.24E-02	2.46E-03	2.44E-07
Resource use, fossils	MJ	2,628,324	2,716,489	2,799	3,132	4.33E-01	4.78E-02	4.76E-06
Resource use, minerals and metals	g Sb eq.	8,025	7,506	8.55	8.66	1.32E-03	1.32E-04	1.23E-08
Particulate matter	Disease incidence	3.24E-02	3.31E-02	3.45E-05	3.82E-05	5.33E-09	5.83E-10	5.76E-14
Total primary energy	MJ	2,790,649	2,882,545	2,972	3,324	4.60E-01	5.08E-02	5.05E-06
Total electricity	MJ	948,612	997,886	1,010	1,151	1.56E-01	1.76E-02	1.77E-06

Table 28: Results summary

[1] After Granada protocol update

With a similar number of bakers and a larger service offer in 2021 than in 2020, the impact of the Tezos blockchain for each transaction appears to lower over time. Indeed, the **energy consumption by the consensus protocol of Tezos appears not to increase proportionally with the increase in the number of transactions**.

Potential impacts are primarily due to baking equipment (about 58% of the impacts), with the exception of mineral and metal use where Internet access equipment is responsible for 55% of the impact. The use of minerals and metals is highly linked to equipment embodied impacts (around 88% of this impact), while energy-related impacts are mainly due to the use phase (78% to 86%).

The Product Environmental Footprint (PEF) methodology developed by the European Commission's Joint Research Center provides normalization factors to calculate and compare the magnitude of the contributions of potential impacts relative to a same reference unit. The normalization factors are expressed per person based on a global value. **Normalized environmental footprint results do not, however, indicate the severity or relevance of the respective impacts.**

Potential impact	Normalization factor		Tezos blockchain protocol potential impact 2021 (in number of person equivalent[1])
Greenhouse effect	kg CO_2 eq. / person	8.10E+03	17
Resource use, fossils	MJ / person	6.50E+04	42
Resource use, minerals and metals	g Sb eq. / person	6.36E+01	118
Particulate matter	Disease incidence / person	5.95E-04	56

Table 29: Normalized results in expressed in person equivalent

At the baking equipment level, **shared resources with cloud computing or single-board computers have 51% to 78% lower greenhouse gas emissions than individual laptops** and using a **second-hand machine enables to reduce the greenhouse effect by as much as 26% and the minerals and metals resource use by 85%**.

Sensitivity analyses were performed to assess how some parameters influence the results.

As energy-related impacts depend a lot on the use phase, the most influential parameter is the location of bakers and the associated electricity mix. The **greenhouse effect impact can vary, compared to the reference situation, from -66% assuming for example a 100% French mix, to +50% with an average world mix**. The LCA takes into account the location-based approach for greenhouse gas emissions, however the implementation of green contracts and renewable energy -- and the availability of complete information associated with them -- could reduce the impact (market-based approach).

Other parameters that significantly influence the results are the following:

- **Allocation of personal network equipment** to baking activity, considering to what extent this equipment is attributable to baking instead of other connected activities (domestic Internet usage, TV, mobile...). Results can reduce from -5% to 53%, when considering 50% to 0% allocation.
- **Electrical intensity of IP network** depending on the hypothesis used, as bibliographic literature gives a wide range of intensities. Results can vary from -19% to +19%, when considering lower and upper bonds.
- **Share of public nodes** as private nodes exchange less data on the network. A private node has between 26% and 28% lower potential impacts compared to a public node (except for element depletion which is similar).

[1] The normalization factor represents the average environmental impact of one person in the world

- **The internet usage**, the quantity of data exchanged on the internet by the baking equipment varied significantly from one baker to another. When considering lower and upper bonds of the data collected on internet usage results can vary from -13% to +18%.

Finally, parameters like PUE of data centers and transport mode of equipment do not significantly impact the results. This is due to the share of cloud and data center-based bakers (41%) and the small share of transport in the results (less than 5% for all the studied impacts).

6. Section VI – Critical review

Detailed comments and answers of the practitioner can be found in Appendix E.

Critical Review Report of the PwC LCA study of the Tezos Blockchain Protocol

Author: Hélène Lelièvre, independent LCA consultant, Enviroconseil, France
Date: 29th November 2021

1. Goal and scope of the critical review

This independent external review was carried out during October and November 2021 on an updated version of the LCA study on the Tezos blockchain protocol that was carried out by PwC on the same period. This LCA study is commissioned by Nomadic Labs who develops and maintains the Tezos blockchain protocol. A first version of the study was performed between February and June 2021 by PwC with a critical review that took place during the summer 2021 (see annex 2). In this updated version of the study, several remaining comments made during the first critical review were taken into account by the practitioner. The update of the study was decided by Nomadic Labs due to the increase of the Tezos blockchain use with much more transactions on the second part of 2021 year. The scope of the LCA study only encompasses nodes run by bakers (the protocol) and not all blockchain nodes: nodes run by bakers and nodes run by other agents.

The external review was performed in a 4 steps process, on the following documents, transmitted by PwC:

- "Study of the environmental impact of the Tezos blockchain, Life Cycle Analysis of the Tezos blockchain protocol", version of 10 November 2021 (for the first round of comments),
- "Study of the environmental impact of the Tezos blockchain, Life Cycle Analysis of the Tezos blockchain protocol", version of 22 November 2021 (for the second round of comments),
- "Evaluation of the environmental impact of the Tezos blockchain, Life Cycle Assessment of the Tezos blockchain protocol", version of the report of 24 November 2021 (for the third round of comments),
- "Study of the environmental impact of the Tezos blockchain, Life Cycle Assessment of the Tezos blockchain protocol", final version of the report of 26 November 2021 (final check).

In addition, several Webex between the reviewer and PwC team were organized to discuss the changes compared to the first version of the study and integrate as much as possible the remaining reviewer's remarks of the first critical review. A review by sampling of the LCA modelling in the TEAM™ LCA software was also performed on the model changes.

The goal of the critical review was to assess the compliance of the LCA study with ISO 14 040 and ISO 14 044 standards. It is mentioned that this LCA does not include a comparison of the Tezos blockchain protocol with other types of blockchains (no comparative assertion as defined by ISO 14 040). It is also mentioned that the reviewer is an LCA expert but not an expert in blockchain technology. As such, the relevance of the IT data used in the LCA model could not be assessed.

2. Main findings and conclusions

The following remarks, emitted during the first critical review were taken into account in the updated study: use of a model linking the volume of exchanged data on internet with the number of transactions on the blockchain (the quantity of exchanged data was considered constant in the first version of the study), use of Ecoinvent models for electricity production instead of older PwC models and use of updated Life Cycle Impact Assessment methods (Environmental Footprint version 3.0, proposed by the European Commission). Most of the reviewer comments were taken into account by the practitioner and the content of the report was improved. An additional sensitivity analysis asked by the reviewer was run on the intensity of electricity usage per quantity of exchanged data for 2020 and 2021. A global uncertainty analysis combining the key data uncertainties could not be run due to the technical limitations of the LCA tool. This would have allowed to better assess the global uncertainty of the LCA results, that is assessed to be higher than classical LCAs due to the structural variability of the data (data from the bakers' questionnaires, data from a few bakers for the exchanged data volume, data on the equipment description and other literature data found on internet).

The LCA study is compliant with ISO 14 040 and ISO 14 044 requirements.

The other key findings of the LCA study review (first review and second review of the updated version) are as follows:

- The scope of the study is only encompassing nodes run by bakers (the protocol), therefore the environmental impacts of the total Tezos blockchain, per transaction and per gas unit is expected to be higher than the LCA results presented in the study due to nodes being run on the network by agents other than bakers (70% more in a measure done by Nomadic Labs in 2021). This limitation is listed in the report.
- The sections of the LCA report presenting the input data and assumptions were not developed enough and this was improved in the final version of the report, thus increasing the transparency of the study.
- The list of excluded steps was completed.
- The LCA model on the end-of-life part (end of life of equipment) is modelled in a simplified way (only the recovered part is taken into account, the rest being considered as landfilled but with no environmental impact associated with this destination). In reality, a fraction may be directly incinerated, leading to additional environmental impacts. For landfilling, in case environmental LCA impacts on soil, water or land use would be added in the scope, the LCA model should be improved.
- The third functional unit concerning running a smart contract was reformulated to be consistent.
- The quality of the data was better described.

For a future study, the 3 following recommendations can be emitted:

- Refine the modelling of the IT equipment end of life;
- Improve the knowledge about the other agents than bakers being on the Tezos blockchain;
- Get more data from bakers linking the volume of exchanged data with the number of transactions. This would allow to refine the link between them and assess more accurately the uncertainty linked to this part of the model.

7. Section VII – References

- ISO 14040:2006 « Environmental management — Life cycle analysis — Principles and framework »
- ISO 14044:2006 « Environmental management — Life cycle analysis — Requirements and guidelines»
- « Product Environmental Footprint Category Rule: IT equipment (Storage) ». 2020. PEFCR. European Commission. https://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_ITequipment_Feb2020_2.pdf.
- We are Social et Hootsuite. « Digital 2021: Global Overview Report ». DataReportal – Global Digital Insights. https://datareportal.com/reports/digital-2021-global-overview-report.
- DAVY, Benjamin. 2021. « Estimating AWS EC2 Instances Power Consumption ». Medium. March 2021. https://medium.com/teads-engineering/estimating-aws-ec2-instances-power-consumption-c9745e347959.
- Spec. « All Published SPEC SPECpower_ssj2008 Results ». https://www.spec.org/power_ssj2008/results/power_ssj2008.html.
- Dr. Bashroush, Rabih, et Andy Lawrence. 2020. « Beyond PUE: Tackling IT's Wasted Terawatts ». Uptime Institute. https://uptimeinstitute.com/beyond-pue-tackling-it%E2%80%99s-wasted-terawatts.
- ADEME. 2012. « Technologies Numériques, Information et Communication – Guide Sectoriel ». https://www.ademe.fr/sites/default/files/assets/documents/ademe-ges-tic-0212.pdf.
- Ascierto, Rhonda, et Andy Lawrence. 2020. « Uptime Institue Global Data Center Survey 2020 ». Uptime Institute. https://uptimeinstitute.com/2020-data-center-industry-survey-results
- George Kamiya. « The Carbon Footprint of Streaming Video: Fact-Checking the Headlines – Analysis ». IEA. https://www.iea.org/commentaries/the-carbon-footprint-of-streaming-video-fact-checking-the-headlines.
- LHOTELLIER, Johan, Etienne LESS, Emilie BOSSANNE, Sandrine PESNEL, ADEME, et RDC ENVIRONMENT. 2018. « Modélisation et évaluation du poids carbone de produits de consommation et biens d'équipement ». ADEME. https://librairie.ademe.fr/consommer-autrement/1190-modelisation-et-evaluation-du-poids-carbone-de-produits-de-consommation-et-biens-d-equipement.html.
- Schumacher, Kelsea A. 2016. « Electronic waste management in the U.S.: practice and policy ». Thesis, University of Delaware. https://udspace.udel.edu/handle/19716/20333.
- ISO/14040 . International Standardisation Organisation, (1997), Environmental management – Life cycle analysis – Principles and framework.

Appendix A. General methods for life cycle analysis

The evaluation of industrial systems is not a recent discipline. The first attempts to analyse the environmental impacts of a product procedure were made in the mid-70s and were centred uniquely on energy aspects[1].

The term "Life Cycle Analysis" or "Analysis" was introduced during workshops organized by the SETAC (Society of Environmental Toxicology and Chemistry). According to standards defined by practitioners, taken up by the SETAC and formalized in national or international standards (AFNOR X 30-300 and ISO 14040 respectively), the environmental analysis of a product is carried out in four phases[2]:

***Definition of objectives and field of research**,* (first definition of the system boundaries, functional unit, data to be collected, etc.),

Analysis of the inventory, phase of the inventory listing the flows of materials and energy (impact factors) for a defined system,

***Analysis of impact**,* phase interpreting and analysing the impacts on the environment, carried out on the basis of figures in the inventory and synthetic indicators, carefully chosen and representative of specific impacts,

Interpretation, phase analysing the procedure, including identification of strengths and weaknesses in the procedure and any analysis of specific scenarios.

The life cycle inventory consists of noting the energy and material flows – or *impact factors* on the environment – within the boundaries of the *system studied.* These flows are related to a unit called the *functional unit.*

The object of this paragraph is to present the various phases of the inventory, from definition of the functional unit through collection of data on site, via definition of the system and choice of allocation rules and rules for taking into account recycling of products at the end of their life.

A.1. The functional unit

The flows listed in the inventories are not calculated on physical product quantity, but on the basis of an equivalent service rendered.

For example, during evaluation of the respective advantages of different types of packaging, 1 kg of glass would not be compared with 1 kg of plastic material, but a comparison would be made between a liter of liquid packaged in either X g of non-returnable glass, Y g of returnable glass (Y being a function of the number of re-uses of the bottles) or Z g of plastic material.

Choice of this unit must be conditioned by the fact that the aim of a product's inventory is to evaluate the impacts of that product on the environment, **fulfilling a given function**. The functional unit must therefore be a **unit of use** and not simply a unit of manufacture (tonnage or volume for example).

This unit, called the "functional unit" in accordance with European LCA inventory terminology, is the basis for calculating the flows assessed.

A.2. Delimitation of the system

The objective of the LCA inventory is to recognize, understand and interpret all the impacts on the environment

[1] Handbook of industrial energy analysis. Boustead I. & Hancock G.F. - Ellis Horwood (1979)
[2] ISO/14040 . International Standardisation Organisation, (1997), Environmental management – Life cycle analysis – Principles and framework.

of a given system which, according to the problem envisaged, can be:

- all the life cycle stages of a given product,
- the stages of a given process, for a given product,
- a production site for a given product.

The flows listed within the boundaries of the system must be directly interpretable in terms of environmental impact. Thus, consumption of gasoil is not directly interpretable, however this consumption corresponds to a particular quantity of crude oil extracted, transported, refined then burnt, with each of these stages having impacts on the environment.

Interpretable flows directly drawn from or discarded into the environment are called **elementary flows**. They can be:

- input into the system: raw materials and certain forms of energy (wind, solar, hydraulic…),
- output from the system: liquid or gaseous waste, final solids and certain energy flows (heat, ionizing radiation, etc.).

These are the opposite of the following **non elementary flows**:

- input into the system: extracted materials, intermediate products, steam, electricity, …,
- output from the system: packaging waste, energy produced, ….

Thus, the system must include the stages enabling these elementary flows to be reached, such as development of intermediate products and the production of consumed energy.

Generally speaking, such a system includes the following stages (as well as transport) that are treated as sub-systems:

- extraction of raw materials and production of the component's parts of the finished product,
- assembly / formulation of the finished product,
- distribution,
- use,
- end of life processing of the product.

More generally, the LCA broadens the system to include the production procedures for each input flow, up to their constituent raw materials.

Output flows from the system must similarly be monitored up to final waste in the natural environment or dumping.

The procedure for broadening the system described above is simple in principle: all the stages enabling ascent to or descent from the elementary flows are taken into account in the system.

However, it cannot be conducted exhaustively for the following reason:

inclusion of all the stages contributing to the life cycle of a product entails study of the whole of the industrial world: construction of capital goods (factories, lorries, ships, etc.…), roads and port infrastructures necessary for transport, etc.…

Thus, the procedures included in the system concerning the development of intermediate products consumed and the discarding of output flows up until their transformation into final waste must be clearly stated.

The choice of boundaries for the system studied – by nature conventional and dependent on the objectives of the LCA inventory – must be based on criteria which are:

- quantitative: for example, percentage of mass or energy content in relation to the mass of the product studied,
- qualitative: for example, toxicity (inclusion of a procedure said to be polluting even if it makes only a minor contribution to the total product).

Integrated into the elementary flows are:

- materials with a non-energy use, consumed on site and for which the extraction or production is not taken into account; these are materials used in small quantities,
- liquid effluent and atmospheric emissions,
- some solid waste products, in the absence of data concerning their discharge procedures.

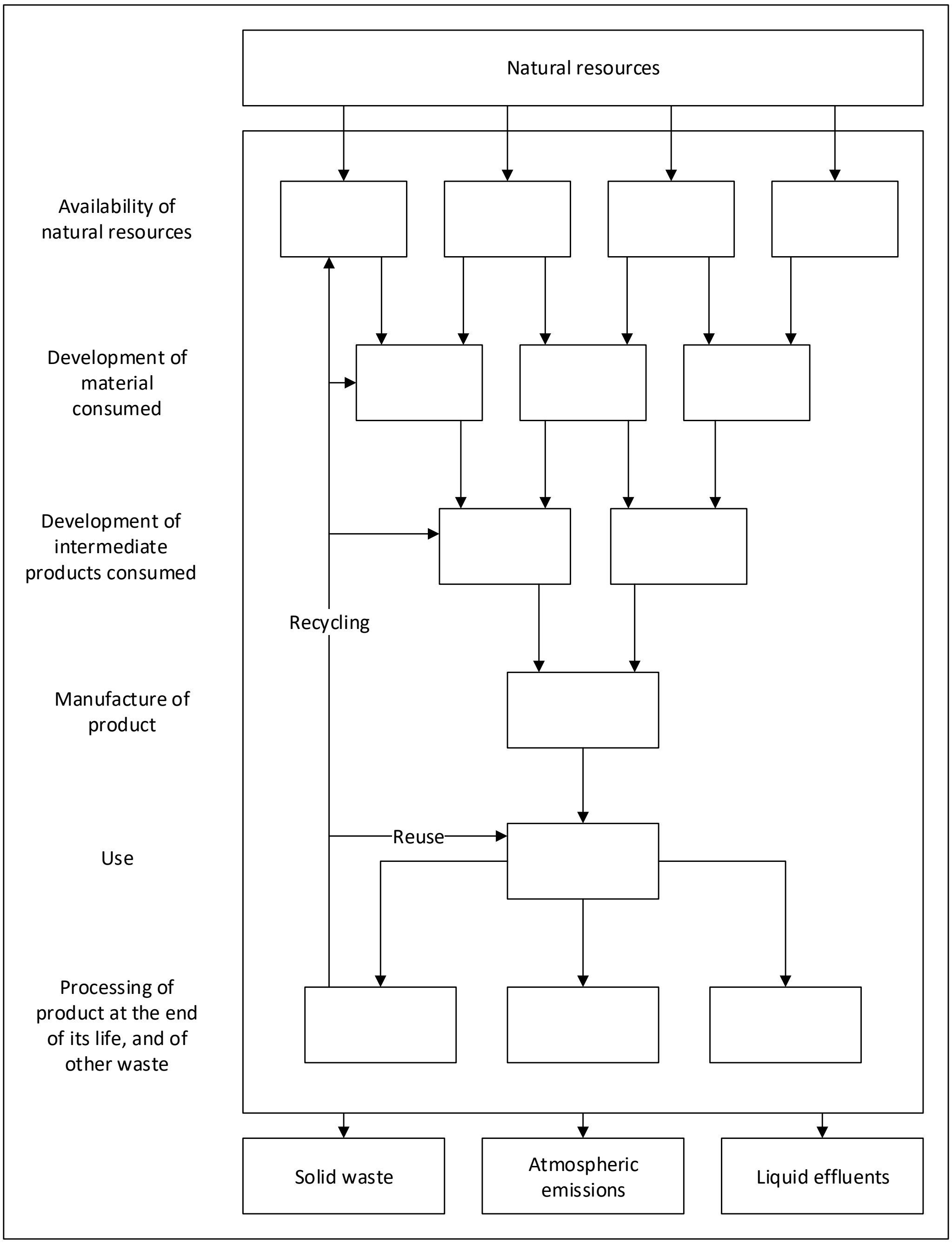

Figure 18: Methodology: Delimitation of the system

Note on capital goods: the following example offers a schematic representation of the (generally negligible) incidence of capital goods on the life cycle of a product (limited to an energy evaluation). The example of steel manufacture has been used to evaluate the cost in energy terms of fabricating a refinery. A refinery processing 6 million tonnes of raw product per annum over 15 years requires around 20 000 tonnes of steel for its construction. The preparation of a tonne of steel requires approximately the energy equivalent of one TOE. The steel working then requires energy of 0.0002 TOE/ tonne of refined oil, or 0.02%, which is negligible compared to the energy consumed in extracting, transporting and refining the oil (around 10% of the energy delivered).

A.3. Data collected

For each stage identified within the system, the following flows (known as impact factors as they are a source of environmental impact) should be listed:

- **energy consumption**, differentiated by origin: electrical energy from the grid, energy from fossil fuels, etc.,
- **consumption of raw materials,** renewable or not (water, ores, etc.),
- **liquid effluent:** suspended matter, chemical (and biological) demand for oxygen, hydrocarbons, nitrates, sulphates, phenols, heavy metals, etc.,
- **atmospheric emissions:** CO, CO_2, NO_x, N_2O, SO_x, CH_4, dust, volatile organic compounds, hydrocarbons, metals, etc.,
- **solid waste**, classified by type (paper, plastic, metal, glass, etc.) or destination (dumping, incineration, recycling, energy recovery, etc.).

This collection of data concerns all the industrial stages included in the system as well as the transport stages, availability of energy (electrical and thermal energy) and consumption of packaging and exterior packaging.

This quantitative data is, first and foremost, that measured by the industrial sites involved in the procedure.

As a last resort, data from other manufacturers producing similar products may be used. This data is then generally of bibliographical origin.

In accordance with the principle of transparency applied to the preparation of LCA inventories, this type of choice is always explained.

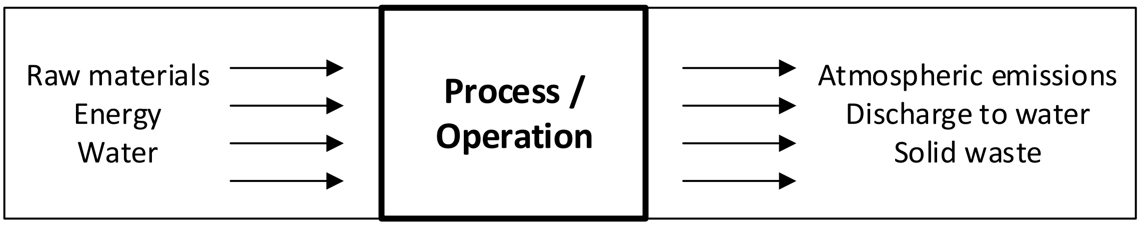

Figure 19: Methodology: data recorded for each module

Bibliographical data may be presented in three forms:

- **"Raw" LCA inventory:** only the final results of the inventory are accessible,
- **documented LCA inventory:** all the information sources are referenced and explained,
- **broken down bibliographical data:** data is distributed between several sources (i.e. each source deals with only one aspect of data). The LCA inventory calculated via this route corresponds definitively to a model which is internal to the company PwC and which can be refined over time.

Data obtained in the latter two cases can be adapted to the analysis of particular procedures.

However, taking into account the relatively recent character of the notion of environmental analysis, the last case is the most frequent. Furthermore, data available in scientific literature often only allows an inventory of material and energy consumption to be drawn up. The origin and nature of the data must be made clear to enable the LCA inventory to be completed once the data is available or measurements have been taken.

To summarize, bibliographical data makes up for the lack of information collected directly from the industrial sites involved. Its use is compulsory for processes where observation on industrial sites is difficult (extraction of gas, oil, production of electricity for example). It offers a significant time-saving and has the advantage of allowing the system studied to be extended to stages which could not have been included without it. However, it is preferable to substitute this for data measured on the industrial sites applicable to the system, wherever this is possible.

A.4. Choice of allocation rules

The industrial systems studied are often multi-product (or multi-function). It is thus necessary to be able to allocate to each of the co-products the impacts incumbent on them, with the aid of allocation rules.

For example, an oil refinery is responsible for bitumen, grease, oil, heavy fuels, gasoil, kerosene and light cuts (naphtha and liquefied petroleum gas: particularly propane and butane).

Generally speaking, a number of processes are responsible for generating the co-products of the chemical industry, since it is rare that a chemical reaction gives rise to the synthesis of only one product. Usually two or even three products are obtained, which may be co-products, or by-products from which energy is likely to be recovered, or even waste with no value.

Where there are co-products, or if some of the by-products of the product studied are subject to energy recovery, the impacts on the environment of the process from which they result must be distributed between the various products.

It is essential that allocation rules are determined in the case of procedures with multiple input flows such as incineration.

Various allocation rules can be used which distribute the process impact factors prorata according to the particular case, to:

- the mass of the products (**mass allocation**),
- the volume of the products (**volume allocation**),
- the number of moles in the products (**molar allocation**),
- the low calorific value of the products (**energy allocation**).

Several rules relating to different impact factors may be used if the physical nature of the phenomena so requires.

Note: the absence of precise data also means that distribution keys must be used without the processes in question generating co-products. This is the case for a factory which manufactures unrelated products in distinct workshops, and which only communicates information relative to the factory as a whole.

A.5. Choice of rules for taking recycling into account

In the life cycle of products within a procedure, numerous recycling loops may exist:

- recycling of manufacturing rejects and scrap,
- incorporation of recycled materials into product manufacture,
- recycling of products at the end of their life, etc.

Cases where a product is recycled within its own life cycle (known as **closed loop** recycling) are directly taken into account in the LCA inventory prepared, via the functional unit.

Thus, a green glass bottle recycled at a rate of 50% post-consumption, will consume an amount of raw materials two times lower than a non-recycled green glass bottle (disregarding the recycling output).

In contrast there is **open loop** recycling – the most frequent – where the initial product is recycled into another procedure, known as a secondary.

In the latter case, different methods exist for allocating the flows associated with the recycling stages and the material savings made between the procedure used for the initial product and that used for the secondary product. Here again there is a choice of rules for allocating and taking into account co-products. Open loop recycling can be considered either as waste processing from the point of view of the initial product, or as a stage in obtaining raw materials from the point of view of the secondary product.

The effects of the recycling operation entail:

- collection of products for recycling,
- the actual recycling process,
- the savings in raw materials in the secondary product procedure,
- adaptation of the processes or products to the use of recycled material,
- waste removal savings in the primary product procedure,
- the differences introduced into the waste removal procedure for the secondary product

Choices, on which the final results depend, must then be made between:

- allocation of all the impacts of recycling to the initial product,
- allocation of all the impacts of recycling to the secondary product,
- distribution of all or some of the impacts of recycling between the initial and secondary products.

Theoretically, the analysis of multi-function systems should rule out these choices.

These rules for delimiting the boundaries of the system are the subject of a publication, acknowledged by the profession and are detailed in the international standard ISO 14040

Appendix B. Secondary data used

B.1. Electricity generation mixes

Source	Austria	Switzerland	Germany	Finland	France	UK	Hong Kong	Ireland	Japan	Netherlands	Russia	Singapore	Canada	China	Global	EU	United States
Biogas	2%	2%	5%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	1%	0%
Biomass	2%	1%	1%	5%	0%	6%	0%	1%	1%	1%	0%	1%	0%	0%	1%	2%	1%
Blast Furnace Gas	0%	0%	0%	1%	0%	0%	0%	0%	1%	2%	0%	0%	0%	0%	0%	0%	0%
Hard Coal	5%	0%	12%	8%	2%	6%	61%	7%	30%	25%	9%	1%	1%	75%	31%	10%	13%
Hydro	45%	69%	4%	25%	12%	2%	11%	2%	8%	4%	19%	0%	58%	17%	17%	18%	7%
Lignite	11%	0%	22%	1%	0%	0%	0%	0%	0%	5%	7%	0%	8%	0%	5%	9%	10%
Natural Gas	12%	2%	9%	9%	5%	38%	26%	48%	37%	37%	45%	94%	9%	2%	24%	15%	37%
Nuclear	8%	20%	13%	36%	71%	24%	2%	1%	6%	6%	20%	0%	16%	2%	11%	26%	20%
Oil	0%	0%	0%	1%	1%	0%	1%	0%	3%	1%	0%	0%	0%	0%	3%	1%	0%
Peat	0%	0%	0%	4%	0%	0%	0%	7%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Photovoltaic	3%	4%	13%	0%	3%	6%	0%	0%	10%	6%	0%	1%	1%	1%	2%	6%	3%
Waste	1%	1%	2%	1%	0%	1%	0%	2%	2%	0%	0%	3%	0%	0%	0%	1%	0%
Wind	11%	1%	18%	9%	5%	17%	0%	30%	1%	12%	0%	0%	6%	3%	4%	11%	7%

Source: IEA for the year 2018 via Ecoinvent.

B.2. Bibliographic sources of secondary data

All Ecoinvent modules are using the cut-off system model.

Packaging

Type of Data	Name of generic module	Source	Year
Paper	Market for printed paper - GLO	Ecoinvent 3.8	2002-2021
Polyethylene, low density	Polyethylene (LDPE, granulate, Europe)	DEAM™	2014
Extrusion plastic film	Extrusion plastic film, RoW	Ecoinvent 3.8	1993-2021
Cardboard	Corrugated CardBoard	FEFCO	2015
Polyurethane	Market for polyurethane, flexible foam - RoW	Ecoinvent 3.8	2011-2021
Polystyrene	Market for polystyrene, expandable - GLO	Ecoinvent 3.8	2011-2021

Transport

Type of Data	Name of generic module	Source	Year
Road Transport	Transport, freight, lorry 16-32 metric ton, EURO3 - RoW	Ecoinvent 3.8	2009-2021
Air transport	Transport, freight, aircraft, all distances to generic market for transport, freight, aircraft, unspecified - GLO	Ecoinvent 3.8	2016-2021
Sea transport	Transport, freight, sea, container ship - GLO	Ecoinvent 3.8	2007-2021

Electronics

Type of Data	Name of generic module	Source	Year
Power supply	Power supply unit production, for desktop computer - RoW	Ecoinvent 3.8	2005-2021
Printed wiring board, mainboard	Printed wiring board production, mounted mainboard, desktop computer, Pb free - GLO	Ecoinvent 3.8	2005-2021
Printed wiring board	Printed wiring board production, surface mounted, unspecified, Pb free - GLO	Ecoinvent 3.8	2005-2021
Integrated circuits, memory	Integrated circuit production, memory type - GLO	Ecoinvent 3.8	2000-2021
Laptop	Computer production, laptop - GLO	Ecoinvent 3.8	2001-2021
LCD Screen / OLED Screen	Liquid crystal display production, unmounted - GLO	Ecoinvent 3.8	2001-2021
Router	Router, internet - RoW	Ecoinvent 3.8	2005-2021
Computer / Server	Computer production, desktop, without screen - GLO	Ecoinvent 3.8	1998-2021

End of Life

Type of Data	Name of generic module	Source	Year
EoL Aluminium	Treatment of aluminium scrap, post-consumer, by collecting, sorting, cleaning, pressing - RoW	Ecoinvent 3.8	2005-2021
EoL Plastic	Treatment of waste plastic, consumer electronics, municipal incineration - RoW	Ecoinvent 3.8	2006-2021
EoL PWB	Treatment of scrap printed wiring boards, shredding and separation - RoW	Ecoinvent 3.8	2005-2021
EoL LCD	Treatment of used liquid crystal display module - RoW	Ecoinvent 3.8	2006-2021

Others

Type of Data	Name of generic module	Source	Year
Electricity	Electricity (*Country*[1], 2015)	Ecoinvent 3.8	2018
ABS (Acrylonitrile-butadiene-styrene)	Market for acrylonitrile-butadiene-styrene - GLO	Ecoinvent 3.8	2011-2021
Aluminium	Market for aluminium, cast alloy - GLO	Ecoinvent 3.8	2011-2021
Steel	Steel production, chromium steel 18/8, hot rolled - RoW	Ecoinvent 3.8	2000-2021

Appendix C. Life Cycle inventory

C.1. Guide to nomenclature of flows

Each line in the following table corresponds to an environmental flow (sections headed “inputs” and “outputs”)

By agreement, certain categories of flow (elementary flows inputting or outputting the systems studied) have a particular notation in their title:

(r) corresponds to consumption of a natural resource drawn directly from the environment. For example, “(r) Oil (in ground)” equates to the consumption of crude oil, whereas “(r) Iron (Fe, ore)” equates to the consumption of iron ore.

(a) corresponds to an emission to air. For example, “(a) Carbon Monoxide (CO)” equates to atmospheric emissions of carbon monoxide.

(s) corresponds to an emission to soil. For example, “(s) Cadmium (Cd)” equates to emissions of cadmium into soil.

(w) corresponds to an emission to water. For example, “(w) BOD5 (Biochemical Oxygen Demand)” represents emissions in the water of DBO5 (biochemical oxygen demand over 5 days).

(ar), (sr) and (wr) correspond to emissions to air, water and soil and from radioactive compounds.

C.2. Life Cycle Inventory

C.2.1. Assembly hypothesis

Energy for the assembly of IT equipment part was calculated based on the Ecoinvent module "Laptop, production". The electricity consumption of this module was allocated to equipment based on their weight. The assembly is assumed to be in China for all equipment with the exception of the Raspberry Pi which is assembled in the United Kingdom.

Example: Ecoinvent Laptop assembly consumption is 1.67 kWh for 3.12 kg of equipment, therefore, assembly of Intel NUC (0.816 kg) is 1.67/3.12 x 0.816 = 0.437 kWh

C.2.2. Equipment model

The modelling of the equipment required some assumptions. There are several types of assumptions that were made:

- The exact packaging of the equipment was not known, then conservative estimations were made using proxies (weight of other packages) or bibliographic resources (ADEME).
- The total weight of the equipment and its composition was known but not the weight of each of its components (example for the Ledger Nano S). In that case, assumptions were made based on other equipment or experience.

Raspberry Pi

Step	Part	Hypothesis	Unit	Value	Source
Production	Mainboard		kg	0.044	Source for weight[1] (46g). Composition is an assumption
	RAM		kg	0.002	
	Assembly	Energy allocation rule (see C.2.1)	MJ / unit	0.089	
	Case	Plastic (ABS: Acrylonitrile butadiene styrene)	kg	0.08	
		Aluminum	Kg	0.08	
	Power supply		Kg	0.142	Amazon[2]
	SSD - External		Unit	1	
Packaging	Polyethylene film		Kg	0.03	Assumption
	Paper		Kg	0.01	Assumption
	Cardboard		Kg	0.15	Assumption
Transport		50% transport (see 3.2.4) / 50% 1000 km road transport (Europe to Europe)			
Use	Power consumption		W	9	See 3.2.2.1
	Lifetime		Year	5	See 3.2.2.1
End of Life	Treatment PWB	See 3.2.5	Kg	0.018	
	Treatment plastic		Kg	0.032	
	Treatment aluminium		Kg	0.032	

Table 30: Model Raspberry Pi

[1] Social Compare. https://socialcompare.com/en/comparison/raspberrypi-models-comparison

[2] Amazon. https://www.amazon.com/ask/questions/TxMDZ1OR8D53RP

Intel NUC

Step	Part	Hypothesis	Unit	Value	Source
Production	Mainboard		kg	0.170	Amazon[1]
	RAM		kg	0.009	Assumption
	Assembly	Energy allocation rule (see C.2.1)	MJ / unit	0.089	
	Case	Plastic (ABS)	kg	0.319	BlackMarket[2]
		Aluminium	kg	0.319	
	Power supply		kg	0.5	SimplyNuc[3]
	SSD - Internal		unit	1	
Packaging	Polyethylene film		kg	0.05	Assumption
	Paper		kg	0.01	Assumption
	Cardboard		kg	0.2	Assumption
Transport		See 3.2.4			
Use	Power consumption		W	12	See 3.2.2.1
	Lifetime		Year	5	See 3.2.2.1
End of Life	Treatment PWB	See 3.2.5	kg	0.072	
	Treatment plastic		kg	0.127	
	Treatment aluminium		kg	0.127	

Table 31: Model Intel NUC

Laptop

Step	Part	Hypothesis	Unit	Value	Source
Production	Laptop	1.2 unit of 12.1 inches laptop because laptop are generally larger today	unit	1.2	Ecoinvent
Packaging		Included in Ecoinvent laptop model			
Transport		See 3.2.4			
Use	Power consumption		W	30	See 3.2.2.1
	Lifetime		Year	5	See 3.2.2.1
End of Life		Included in Ecoinvent laptop model			

Table 32: Model laptop

[1] Amazon. https://www.amazon.com/Intel-BLKNUC7I5DNBE-NUC-BOARD-NUC7I5DNBE/dp/B078BGNRX5
[2] Black Market. https://www.backmarket.fr/intel-nuc-kit-nuc5cpyh-celeron-16-ghz-ssd-120-go-ram-8-go-pas-cher/463053.html?shopping=gmc&gclid=CjwKCAjw07qDBhBxEiwA6pPbHsCsPIGkjzF_4mUInGX9btpEa9rUAhu491FMKV2g44lTO1DAcRaG-BoCKoIQAvD_BwE
[3] SimplyNuc. https://simplynuc.co.uk/product/120w-power-supply/

Second-hand laptop

Step	Part	Hypothesis	Unit	Value	Source
Production	SSD internal		Unit	1	
Packaging	Cardboard		kg	0.358	Ademe[1]
	Polyethylene film		kg	0.047	
	Paper		kg	0.018	
Transport		See 3.2.4			
Use	Power consumption		W	30	See 3.2.2.1
	Lifetime		Year	3	See 3.2.2.1

Table 33: Model second-hand laptop

Ledger Nano S

Step	Part	Hypothesis	Unit	Value	Source
Production	Plastic (ABS)		kg	0.008	Composition and total weight: Ledger[2] Components weight: Assumption
	Stainless steel		kg	0.002	
	PWB		kg	0.005	
	OLED Screen		kg	0.002	
Assembly		Energy allocation rule (see C.2.1)	MJ / unit	0.031	
Packaging	Cardboard		kg	0.14	Assumption
	Polyethylene film		kg	0.005	Assumption
Transport		See 3.2.4			
Use	Power consumption		W	0.135	See 3.2.2.1
	Lifetime		Year	5	See 3.2.2.1
End of Life	Treatment PWB	See 3.2.5	kg	0.002	
	Treatment plastic		kg	0.0032	
	Treatment LCD		kg	0.0008	

Table 34: Model Ledger Nano S

[1] LHOTELLIER, Johan, Etienne LESS, Emilie BOSSANNE, Sandrine PESNEL, ADEME, et RDC ENVIRONMENT. 2018. « Modélisation et évaluation du poids carbone de produits de consommation et biens d'équipement ». ADEME.
[2] Ledger https://shop.ledger.com/products/ledger-nano-s

Router / Network equipment

The model considered for the router and the network equipment (switches and firewall) consists of the router model from Ecoinvent with an integrated circuit of memory type that is not included in the Ecoinvent model.

Step	Part	Hypothesis	Unit	Value	Source
Production	Router		unit	1	Ecoinvent
	Integrated circuit, memory type		kg	0.02	Assumption
Packaging	Cardboard		kg	0.436	Ademe[1]
	Polyethylene		kg	0.0013	
	Polyethylene film		kg	0.009	
	Polystyrene		kg	0.256	
	Polyurethane		kg	0.017	
	Aluminum		kg	0.0017	
	Paper		kg	0.111	
Transport		See 3.2.4			
Use	Power consumption		W	10	See 3.2.2.1
	Share of use for baking activities		%	77%	See 3.2.2.2
	Lifetime		Year	5	See 3.2.2.1
End of Life	Treatment PWB	See 3.2.5	kg	0.038	

Table 35: Router model

[1] LHOTELLIER, Johan, Etienne LESS, Emilie BOSSANNE, Sandrine PESNEL, ADEME, et RDC ENVIRONMENT. 2018. « Modélisation et évaluation du poids carbone de produits de consommation et biens d'équipement ». ADEME.

SSD Disk

Step	Part	Hypothesis	Unit	Value	Source
Production	PWB		kg	0.006	Toms Hardware[1]
	Integrated circuit, memory type		kg	0.009	
	Electricity	Energy allocation rule (see C.2.1)	MJ	0.135	
	Case	Aluminum	kg	0.0275	Amazon[2]
		Plastic (ABS)	kg	0.0275	
Packaging	Cardboard		kg	0.15	Assumption
	Polyethylene film		kg	0.05	Assumption
	Paper		kg	0.01	Assumption
Transport		See 3.2.4			
	Lifetime		Year	5	See 3.2.2.1
End of Life	Treatment PWB	See 3.2.5	kg	0.006	
	Treatment aluminium		kg	0.011	
	Treatment plastic		kg	0	

Table 36: SSD disk model

[1] Toms Hardware. https://www.tomshardware.com/features/ssd-vs-hdd-hard-drive-difference#:~:text=Contrastingly%2C%20SSDs%20actually%20get%20faster,(0.01%2D0.02%20pounds).
[2] Amazon. https://www.amazon.com/QNINE-External-Weight-Portable-MacBook/dp/B07P1XLZHP

Data center and cloud

Details and sources can be found in 3.2.2.3

Step	Part	Hypothesis	Unit	Enterprise Data center	Cloud - Dedicated machine	Cloud - Shared machine
Production (one server)	Computer, desktop without screen		kg	40	40	40
	SSD disk - Internal		unit	16	16	16
	Rack - Steel		kg / server	8.1	8.1	8.1
	Network equipment		unit / server	0.9	0.9	0.9
		Included in Ecoinvent model				
Transport		See general hypotheses				
Use (one node)	Power consumption - Server (per node)		W	14	14	7
	Power consumption - Network equipment (per node)		W	0.56	0.56	0.56
	Number of nodes per server	Server with 256 GB of RAM	nb	16	16	16
	PUE (Power usage effectiveness)		ratio	1.7	1.2	1.2
	Total consumption per node		W	24.76	17.48	9.08
	Lifetime		Year	5 (15 for rack)	5 (15 for rack)	5 (15 for rack)
End of Life		Included in Ecoinvent model				

Table 37: Datacenter node model

Cloud HSM

Power consumption of the Cloud HSM is a conservative assumption based on a study by Teads Engineering[1].

Step	Part	Hypothesis	Unit	Value
Production / Packaging / Transport / EoL (one server)		Same as the server running nodes		
Use	Power consumption - per HSM		W	5.6
	Power consumption - Network equipment (per node)		W	0.14
	Number of cloud HSM in one server	Server with 256 GB of RAM	nb	64
	PUE (Power usage effectiveness)		ratio	1.2
	Total consumption per node		W	6,89
	Lifetime		Year	5 (15 for rack)

Table 38: Cloud HSM model

C.2.2. Cloud shared resources efficiency

Numbers from Uptime Institute's study: "Beyond PUE: Tackling IT's Wasted Terawatts" numbers on higher cloud efficiency in the cloud:

	On premise – not virtualized	Cloud - virtualized
Average data center server load	10%	40%
Energy consumption of a 200-million ssj_ops[2] workload (in megawatt-hours) (server only, PUE effect not included, equipment not older than 6 years)	369.38	178.5

Table 39: Cloud shared resources efficiency gains

There is a 51% reduction in power per operation in the cloud virtualized environment before the effect of a lower power usage effectiveness.

[1] DAVY, Benjamin. 2021. « Evaluating the Carbon Footprint of a Software Platform Hosted in the Cloud ». Medium. March 2021. https://medium.com/teads-engineering/evaluating-the-carbon-footprint-of-a-software-platform-hosted-in-the-cloud-e716e14e060c.

[2] Ssj_opps refers to server-side Java operations, it is the workload given to the server during the benchmark to measure its efficiency.

Appendix D. Questionnaire

Tezos environmental analysis

Dear baker,

We are working on publishing a paper that estimates the environmental footprint of the Tezos blockchain based on bakers' equipment and electricity consumption. We believe that this paper will be a differentiating factor for Tezos, which will encourage its large-scale adoption.

To make a scientific and quantitative report, we need detailed information to estimate the life cycle of the Tezos blockchain, and calculate the carbon footprint of the Tezos protocol. Nomadic Labs teams and our partner's team (4 experts of a big four company subject to NDA, who will support the data collection and analysis) will be the only ones to have access to your data, which will be anonymised and protected in a secure environment compliant with GDPR requirements. For the publication of the report, your data will be presented in an aggregated and anonymised format.

Questions about your set-up will enable to estimate the emissions linked to equipment production. Questions about your usage and your location will enable to estimate the energy mix and the emissions linked to energy consumption. Finally, we ask your Tezos address. This is only to reconcile answers from this questionnaire and data we gather from APIs in order to build our analysis on a comprehensive set of data. If you are not willing to share any data, just skip the question, but keep in mind that we'll take care of your data, and we ask every data point only to ensure our analysis is as documented as possible.

Your participation will be very helpful and it should not take more than 5 minutes.

The study refers to the year 2020 unless otherwise stated.

As this is a high priority project, it would be most appreciated if you could answer this questionnaire by the end of the month. Again, if you have any concerns about a question, please feel free to move on to the next question. May you have any trouble with the questionnaire, feel free to contact us.

Thank you very much for your time !

Baking equipment

All questions refer to the year 2020 except where stated otherwise

1. How many nodes are you running along with your baker?

2. How many private nodes are you running?

3. How many public nodes are you running?

4. What kind of equipment are you using to connect to the network for baking?

Check all that apply.

- [ ] Single board computer (Raspberry Pi, ...)
- [ ] Personal computer (brand new machine)
- [ ] Personal computer (second-hand purchase)
- [ ] Cloud computing service - Virtual Machine(s) (AWS, Google, Digital Ocean, ...)
- [ ] Cloud computing service - Physical Machine(s) (AWS, Google, Digital Ocean, ...)
- [ ] Enterprise data center (Physical Machines)

Other: [ ] ____________

5. What are the exact models of equipment you are using (hardware models)? Or which exact offer if you are using a cloud service (describe the offer or you can paste a link if more convenient)?

This data is valuable to derive the carbon emissions linked to IT equipment production and transportation. If you are not willing to share this information, you can skip the question.

6. How old is you equipment?

(in month)

7. Where is your equipment located? (countries / states)

Keep in mind we want to be able to determine your energetic mix, not ringing at your door ;)

8. Are you using a kind of specific equipment / software to sign in a secure way?

Check all that apply.

- [ ] In house Hardware Security Module (HSM) (Ledger, ...)
- [ ] Remote signing (cloud HSM)

Other: [ ] ____________________

9. What is the exact model of equipment or solution you use for signing?

AND again, this data is valuable to derive the carbon emissions linked to IT equipment production and transportation. If you are not willing to share this information, you can skip the question.

____

____

____

____

____

10. How old is your equipment for signing?

(in month)

____

11. Where is your equipment for signing located? (countries / states)

AND keep in mind we still only want to be able to determine your energetic mix, not ringing at your door.

____

12. Is there any other information on your set-up you believe is relevant for this environmental study and you want to share with us? (ex. other devices, precision on your set-up...)

____

____

____

____

____

Energy consumption

All questions refer to the year 2020

13. How often are you using your equipment for other purposes than connecting to the network for baking?

Mark only one oval.

- ◯ Never (0%)
- ◯ Sometimes (25%)
- ◯ Regularly (50%)
- ◯ Often (75%)
- ◯ Always (100%)

14. If you bake on personal devices, do you ever turn them off?

Mark only one oval.

- ◯ Never
- ◯ Sometimes
- ◯ Always when I know that I won't bake
- ◯ Other: ______________________

15. If you know it, how much electricity does your baking activity consume?

in kWh or currency (please precise the unit and the period of the data, ex. daily, monthly, annual consumption...)

____

16. Is there any other information on your energy consumption you believe is relevant for this environmental study and you want to share with us? (ex. green energy contract, precision on your consumption profile...)

General

17. When did you start baking?

Example: January 7, 2019

18. Are you still baking?

Mark only one oval.

- ( ) Yes *Skip to question 24*
- ( ) No *Skip to question 23*

19. How many rolls are you baking with?

Mark only one oval.

- ( ) 1 to 50
- ( ) 50 to 100
- ( ) 100 to 500
- ( ) 500 to 1000
- ( ) 1000 to 2000
- ( ) More than 2000

20. What are the history modes of your nodes? (multiple choices possible)

Check all that apply.

- [ ] Rolling
- [ ] Archive
- [ ] Full

21. Have you move your baking service to an other address in 2020?

Only to remove inactive accounts :)

Mark only one oval.

- ( ) Yes
- ( ) No
- ( ) Other: ____________

22. What is your Tezos baking address?

Your answer to this question would help us reconcile answers from this questionnaire and data we gather from APIs in order to build our analysis on a comprehensive set of data, which will be anonymised and protected in a secure environment compliant with GDPR requirements.

____

Stop baking

23. When did you stop baking?

____

Example: January 7, 2019

24. Could we contact you to get more information on the environmental impact of the Tezos blockchain?

Mark only one oval.

- ( ) Yes
- ( ) No

  Skip to section 8 (Your data will be aggregated and anonymised for the study results.)

Appendix E. Detailed comments and answers of the practitioner

3. Annex 1: detailed comments and answers of the practitioner of the 3 rounds of review

LCA External review completed on 18th of November 2021 by Hélène Lelièvre, Enviroconseil, Independent LCA consultant, first round

Document reviewed: Study of the environmental impact of the Tezos blockchain, Life Cycle Analysis of the Tezos blockchain protocol, 10 November 2021

N°	line number	paragraph, figure, table	type (editorial, general, technical, data)	Comment	Recommandation	Practitioner's Answer
1	8	First page	E	Update the date of the methodological report: 10 November 2021 instead of 3 September 2021		ok
2	156	Exe summary		"and running one gas unit of smart contract 2.4E-3 g CO2 eq. in 2020. " The FU for gas of smart contract mentioned a few rows above is "consuming".	Be coherent between the 2 FUs	ok
3	157	Exe summary	E	"The total emission carbon footprint of ": expression is not adapted	Replace by "total carbon footprint"	ok
4	158	Exe summary	G	"The total emission carbon footprint of the blockchain protocol for the 6 million transactions in 2020 is equivalent to the footprint of around 24 European citizens[1]".	It should be updated with 2021 period	ok
5	158	Exe summary	D	footpage note: add the link to the web site where this information is available		ok
	174	Exe summary		"The study considers the impact of Tezos core protocol, and there are many applications build around the protocol which are not included in this study. "	Add "Also, the impact of the end users of the blockchain (using the blockchain for a smart contract) is not included". This should be also listed in the exclusion from the system and justified (figure 3 and section 2.3.2)	- Added to the exec sum - in fig 3 and secion 2.3.2 only the exclusion from inside the system boundaries are listed
6	174	Exe summary/Third bullet of data collection	E	add "the" before "quantity of data exchange"		ok
7	174	Exe summary	G	"PwC has not audited or verified the information provided to them within the scope of the work, regardless of its source, unless specified in this study"	Remove "unless specified in this study" as in the rest of the report no audit is mentioned	ok
8	174	Exe summary		"has had sight of": English wording not clear	replace by another expression	ok
9	200	1.1. Context of the LCA study	G	For clarity, introduce the fact that in 2021, the number of transactions, gas quanity linked to smart contracts increased a lot + the Granada update (linked to that ?) and that several periods are then covered in the study. Create a new section 1.2 Evolution of the blockchain between 2020 and 2021 where graphs on this evolution are presented ? or otherwise, a few sentences + a description in a new section after 2.2.2		Section 1.2 added
10	284	2.2.1. Functional units	E	"En is the environmental impact of the average node on the Tezos blockchain."	replace "average node "by average baker node"	ok
11		2.2.1. Functional units	T	"N is the number of bakers' nodes on the Tezos blockchain."	Add the formula N total = N public + N private and N public or private= average number of node per baker (public or private) x number of active bakers on a year	Added, but not sure if necessary
12	299	2.2.1. Functional units	E	Et in the formula but ET below the formula	homogenize the scientific notation	ok
13	307	2.2.1. Functional units	E	"multiplied by the gas unit "	replace for clarity by "the number of gas unit"	ok
14	309	2.2.1. Functional units	T	"On the Tezos network gas refers to the cost necessary "	add "(in tez)" after cost necessary + comma after "On the Tezos" ("On the Tezos network, gas…")	comma ok (in tez) => could be interprated as 1 gas unit = one tez. So not sure
15	311	2.2.1. Functional units	E	"The results for "	replace by "The LCA results"	ok
16	312	2.2.1. Functional units	E	historic	replace by "historical"	ok
17	313-319		G	Section not clear enough	List for each FU, the periods that are studied. Eg For the impact per baker node: 2020 and 2021 For the impact per transaction : 2020 and 2021 For the impact per gas unit: 2020, 1st Jan-5 August 21, 6 August 21-31th December I wonder if relevant to present LCA results per unit of gas before the Granada update as it is no more relevant and furthermore, due to the change in definition of the gas, the results are not comparable. It complexifies the report and add confusion	I added the periods in each FU paragraph. The integration of the historical value for the gas in the report will be very light (not in exec sum and not in main result table).
18	316-318	2.2.1. Functional units		"Results for the year 2021 are based on data collected from January to the 24th of October and extrapolated over a one-year period (using the average transaction and gas consumption between the Granada protocol update – 6th of August – and the 24th of October)." Not so clear how the results are calculated	Add "for the rest of the year" before "using the average transaction" . Furthermore, for clarity of the whole report and how results are calculated, I would suggest to add somewhere a section describing how each series of results are calculated and from which year each term of the formula is calculated . Maybe a new section 3.3.3 with detailing again each formula presented in section 2.2.1 (and for the FU per node, resplit by making appearing the parameter number of transactions for the internet use	- The periods over which each FU is studied are now split into their respective sub-sections. - "from which year each term of the formula is calculated" => To be discussed, not clear to me
19	462	2.3.2.2. List of excluded lifecycle stages	T	"landfilling mostly affects indicators related to water pollution."	add "and land occupation/transformation"	ok
20	509	2.4.2. Environmental life cycle impact indicators, Table 1	T	Mention the version of the EF indicators chosen (3.0, advised)		ok
21		2.4.2. Environmental life cycle impact indicators, Table 1	T	Mention a link to the EU web site where the EF characterisation factors can be found		ok
22		2.4.2. Environmental life cycle impact indicators, Table 1	T	For climate change, mention the version of the IPCC report on which the EF 3.0 is based		ok
23		2.5 2.5. Requirements relative to precision	T	"This study aims to analyze the environmental matters related " - environmental matters to be rephrased	suggestion: replace by "potential environmental impacts"	ok
24			E	"(more data on the data…)" ; repetition	suggested change: "more information on the data"	ok
25		Table 2	D	mention what is DEAM		ok

N°	line number	paragraph, figure, table	type (editorial, general, technical, data)	Comment	Recommandation	Practitioner's Answer
26			D	mention which packaging components are coming from DEAM		It is precised in the section 3.1
27			D	"raw materials models for IT"	suggested rephrasing: "bills of materials (in components and materials) from Ecoinvent version 3.7.1	ok
28	515	Table 2	D	Remove "TzKT" as this chain explorer was finally not used		ok
29	519		G	rechange "study" in "report" - The calculations were not checked		ok
30	523		G	"The external review took place from June to September 2021. "	Update this sentence with explaining that the study has been updated and that new rounds of criticial review have been organized from October to December 2021	ok
31	537	3.1. Data collection	D	"A questionnaire was sent to bakers and answers were collected from March to April 2021. 70 bakers responded and 69 answers could be exploited for this study"	Add the total number of bakers assessed in 2021 + % represented by the 69 bakers	Added as 17% (69/411) Can be a little imprecise because 411 is the average number of active bakers over the year. The number of active baker over the
32	564	3.1.1 On the number of nodes on the Tezos blockchain, Table 4	T	Add a footnote at "Number of nodes included in the model" to explain it is calculated as nber of nodes per baker x nber of bakers, separately for the public and private nodes or refer to section FU where normally it has been now explained (comment n°11)		I do not think that we should add a footnote as the goal of the is precisely to explain how the number of node is calculated. I added some extra information in the column label to make it
33	585	3.2.1. Development	E	Explicit what means FTE		ok
34	587	3.2.2. Running nodes	T	Title : Change by "Running bakers node" as only baker nodes are included in the main study		ok
35	589	3.2.2. Running nodes	T	Specify what is covered by the embodied impact, not classical term in LCA studies		
36	589	3.2.2. Running nodes	T	$Impact = (Equipment\ embodied + Equipment\ use + Internet\ Use) \times Number\ of\ nodes$	In the formula, adding the term impact for each term would increase the lisibility of the formula	ok
37	589	3.2.2. Running nodes	T	For the first FU, the impact is per baker node so why multiplying by N ?	Remove N in the formula and specify impact per node	equipment embodied+Impact equipment use+Impact internet Us
38	593	3.2.2. Running nodes	T	"the impact of the different components, "	replace by "the impact of the production and assembly of the different components"	ok
39	698	Table 9	D	mention in bracket how many servers per rack are considered		ok
40	698	Table 9	T	detail the calculation of the column "Maximum annual footprint for one node (g CO2 eq.)" in a note or a sentence below the table		ok
41	698	Table 9	G	As a reminder, to be updated with new CO2 result		done
42	718	Table 10	D	Please send the split for the other European countries: is it possible to apply the relevant electricity mix (now Ecoinvent is used, it should be easy to use the right electricity mix for the other countries)		done
43	721		E	"This electrical mix is applied to the devices running nodes"	Add in bracket "baker equipement and internet access	ok
44	734	3.2.2.5. Internet use	D	"To estimate the yearly network traffic of a node, the network traffic of three different bakers (5 nodes) was analyzed:"	Explain how these particular bakers were selected	ok
45	736	3.2.2.5. Internet use	G	The "Company provided data over a one-month period over April and May 2021 and over eight days in October 2021. "	Suggested change "The company provided data for one baker working with it but baking on personal time"	One baker, contacted by the company
46	733-758	3.2.2.5. Internet use	D/T	Insert the values found from the bakers analysis in a table (fixed part and slope) to see the variability of the parameters calculated from the data of the 3 bakers that supplied them	And add a sentence stating that there is a high uncertainty on this average relation	added in a table
47	757	3.2.2.5. Internet use	E	"estimation put the network traffic of a private node at between 0.5% to 2% of the one of a public node." strange wording	Reformulate the sentence in English : "with this estimation, the data exchange of a private node represents between …"	ok
48	754	3.2.2.5. Internet use	T	"The analysis of the network exchanges of the three bakers suggested that the network exchanges quantity is divided into two components"	Add "(linear function)" at the end of the sentence	added in the table
49	755	3.2.2.5. Internet use	T	"With one point of data only, the uncertainty is very high for private node"	"One data point" is not adapted. In reality, "2 data points from one baker"	ok, adapted
50	773		D	"The network traffic was estimated using the average of download and upload to avoid double counting."	Add "(as this is a peer-to-peer network)"	ok
51	775	3.2.2.5. Internet use	T	"This table presents the average internet traffic generated by one node over the different periods studied:"	Add "using the formula that was determined before"	table changed to replace the equations
52	776	3.2.2.5. Internet use, Table 11	D	Add a column with the % of evolution between 2020 and 2021		ok
53	825	3.2.3. Electricity generation models	D	"The modules from Ecoinvent were used to model electricity consumption. The shares of electricity technologies are valid for the year 2018"	On Ecoinvent websites, reference year is said to be 2017 except for US and Canada for which it is 2018 See https://ecoinvent.org/the-ecoinvent-database/data-releases/ecoinvent-3-7/#1610466712317-fe0cb20b-4740 Correct the date	3.8 was used for all modules following update

LCA External review completed on the 24th of November 2021 by Hélène Lelièvre, Enviroconseil, Independent LCA consultant, second round

Document reviewed: Study of the environmental impact of the Tezos blockchain, Life Cycle Analysis of the Tezos blockchain protocol, 22 November 2021

N°	line number	paragraph, figure, table	type (editorial, general, technical, data)	Comment	Recommandation	Answer
54		Title first page	G	"Life cycle analysis"	change "analysis" by "assessment"	ok
55	141		G	"The present report aims at analyzing these impacts through a **life-cycle analysis (LCA) approach**"	change "analysis" by "assessment"	ok
56	152		D	"The analysis is based on **data collected from bakers from mid-March to end-April 2021**"	Change by "data collected from a panel of bakers"	ok
57	154		G	"The following indicative results consider the bakers' nodes"	Change by "consider only the bakers' nodes"	ok
58	168		E	The normalization factors are expressed per capita	change "per capita" by "per person", more explicit	ok
59	171	exe summary, table 2	G	"Table 2: Normalized results in expressed in global persons": Global person difficult to understand for a non LCA practitioner	Change in "Person equivalent" and add a note to explain that this is the average environmental impact of a person in the world	ok
60	171	exe summary, table 2	G	Title of the column "Blockchain potential impact (in global person)"	change "in global person" by "in number of equivalent person"	ok
61	171	exe summary, table 2	G	Mention the year considered for these results		ok
62	171		G	Put in this table the 2020 year to see the evolution of the total blockchain impact. Indeed, having only the results per node and per transaction (table 1) is otherwise misleading on the total impact of the blockchain		ok
63	180		G	Add in the limitations dealing with the scope of the sudy that the end of life of the equipement is modeled in a simplified way		ok
64	349	1.2. Recent evolutions on the Tezos blockchain	E	"The second one is the Granada protocol update that was implemented on the blockchain in August 2021."	Add that this change is described after	This section focuses on two evolution. The first one…, the second one…
65	371	1.2. Recent evolutions on the Tezos blockchain, Granada protocol update: modification of the gas cost of transactions	G	"This fee was reduced"	Add (information available on the link) that the gas consumed has been reduced by a factor of three to six in the execution of already deployed contracts.	ok
66	374	1.2. Recent evolutions on the Tezos blockchain, Granada protocol update: modification of the gas cost of transactions	E	"The consequence of this update for this study is that the 3rd functional unit: "consuming one gas unit for a smart contract" is not comparable between before and after the update."	"after the update": change by "after the Granada update" to be clear	ok
67		Figure 3: Gas to transaction ratio in 2021	T	title of Y axis not very clear : "Daily gas over transaction ratio"	Change by "number of gas units per transaction (daily average)"	ok
68	377	1.2. Recent evolutions on the Tezos blockchain, Granada protocol update: modification of the gas cost of transactions	G	"Because of these evolutions several periods are covered in the study with different results. "	change "with different results" by "to calculate the LCA results over different periods"	ok
69	377-379	1.2. Recent evolutions on the Tezos blockchain, Granada protocol update: modification of the gas cost of transactions	E	"These periods can be the year 2020 or 2021 but also the year 2021-before the Granada update and the year 2021-after the Granada update"	change "can be" by "are"	ok
70	377-379	1.2. Recent evolutions on the Tezos blockchain, Granada protocol update: modification of the gas cost of transactions	G	"These periods can be the year 2020 or 2021 but also the year 2021-before the Granada update and the year 2021-after the Granada update"	change "but also" by "and also, for the LCA result per unit of gas, the 2021 year before…"	ok
71	695	2.4.2. Environmental life cycle impact indicators	E	"Table 1 : Environmental impact indicators"	Change by "List of selected environmental impact indicators"	ok
72		Table 3: Quality matrix	D	2020 is not adapted for the location of baker nodes given by the cartographer node run by Nomadic Labs (it is April 2021)	Mention 2020 (for development of protocol) and 2021 (location of bakers nodes)	ok
73	907	3.2.2.4 Location of the nodes	G	Change by "Location of baker nodes"		ok
74	907	3.2.2.4 Location of the nodes	D	"The node location was collected by the Company using…"	Can you confirm only the bakers nodes were considered in this analysis ?	This is the location of all nodes and the distribution is applied to b
75	944	3.2.5. Internet use	G	"The following table states the observed correlation between transactions and data exchanges."	Mention in bracket "data exchange is the the sum of upload and download"	Added but with the average

N°	line number	paragraph, figure, table	type (editorial, general, technical, data)	Comment	Recommandation	Answer
76	945	Table 12: Data collected from bakers on internet usage	D	(table) Data per transaction (KB / transactions) – Data fixed (GB / day) Baker 1: 5.3 – NA Baker 2 – public node: 3.13 – 1.16 Baker 3: 17.3 – 2.94 Baker 2 – private node: 0.365 – 0 Average value used in the model: 0.375 – 2.05	Mention the type of node for baker 1 and baker 3. Values to be revised: mix of values before dividing by 2 and after dividing by 2	ok
77	945		D		Put 2 lines, one for the average public node, one for the private node (indicating this in bracket) with the values used for the calculations	ok
78	945		D		Average for public node is not correct. The simple average of the 3 values is calculated as 8.58 kB/transaction or 9.17 kB/transaction if values are the sum of upload and download	ok
79	945		T	"as with this estimation, the data exchanges of a private node represent between 0.5% and 2% of the one of a public node."	to be checked again with correct values	ok
80	956	Table 13	E	"Data per transactions (public)"	change by "public node" same for line below : "private node"	ok
81	896	NB: row numbers expressed from now on the version with accepted modifications		"The baking equipment (embodied or use)"	change by "(embodied and use)"	ok
82	896	4.2.1. Results for one node	T	"The baking equipment (embodied or use) is the primary source of potential environmental impact for every indicator considered": not true for the resource (minerals and metals) for which the first source is the internet equipment	Rephrase the sentence	ok
83	898		T	"For instance, the baking equipment is the source of 65% of the resource use of minerals and metals, "	65% not correct (42% with table 16)	corrected
84	899		T	"85% of that being linked to the embodied impact. Regarding greenhouse effect, 60% of emissions are originating from the baking equipment, 85% of these are linked to its electrical consumption during the use phase and 15% is the embodied emissions from the raw material acquisition, manufacturing, transport, packaging and end-of-life."	85%: 83% with table 16	85% is correct
85	910	4.2.2. Results for the blockchain, Table 17	G	Gas row	Add a note below the table reminding that the qty of gas number is not comparable between 2020 and 2021 due to the change in the definition of a gas unit (ex Gas* with *xxxx below the table)	ok
86	915	4.2.2. Results for the blockchain	G	"With a similar number of bakers and a larger service offer, the impact of the blockchain for each transaction or gas unit consumed is lowering (see Figure 9)": No conclusion can be drawn for the FU per gas unit due to the change in the gas unit definition between 2020 and 2021	Rephrase the sentence	ok
87	915	4.2.2. Results for the blockchain	G	"With a similar number of bakers and a larger service offer, the impact of the blockchain for each transaction or gas unit consumed is lowering (see Figure 9)": No conclusion can be drawn for the FU per gas unit due to the change in the gas unit definition between 2020 and 2021	Add some comment on the evolution for the whole blockchain (little increase between 2 and 5% except for resource use (minerals and metals) for which -6% (explain why this differs from the other indicators)	ok
88	919-220	4.2.2. Results for the blockchain	G	"the impact of the core protocol per transaction or unit of gas consumed lowers "	same remark as before, remove the conclusion for the impact per unit of gas	ok

N°	line number	paragraph, figure, table	type (editorial, general, technical, data)	Comment	Recommandation	Answer
89	922	Figure 9: Evolution of potential greenhouse impact between 2020 and 2021	E	For **one node the emissions increased by 11%** due to the increase in network traffic. This resulted in **a 3% augmentation of the blockchain greenhouse effect**, the increase of the node impact being partly offset by the decrease of the number of bakers. Due to the explosion of the number of **transactions and gas** spent on Tezos both of these functional units GHG impact **were reduced by more than 85%.**	"Augmentation" in the title of the slide to be replaced by "increase" offsetted	ok
90	922	Figure 9: Evolution of potential greenhouse impact between 2020 and 2021	E	"one node" in the title of the first part of the graph	change by "one baker node"	ok
91	922	Figure 9: Evolution of potential greenhouse impact between 2020 and 2021	E	"greenhouse impact"	replace by "greenhouse effect" to be homogeneous in wording	ok
92	961	4.3.1.1. Test of model sensitivity to the electrical mix	T	"The model is very sensitive to the electrical mix powering the bakers' equipment. "	add "and the internet network" as the average electricity mix was also used for this part. Can you confirm both parts are covered by	ok, indeed we can confirm.
93	971	Figure 13: Test of model sensitivity to router allocation hypothesis	T	**The internet personal equipment is responsible for 53% of minerals and metals use in the default scenario.**	55% can be read in figure 8, please correct	53% is correct. It is personal internet equipment, thefore not counting internet equipment in cloud which is not affected by
94	992	4.3.1.4. Test of model sensitivity to the quantity of data exchanges over the Internet	G	"As explained in section 3.2.2.5, the reference model considers two components that determined network traffic of nodes: "	change by "the reference model considers that the exchanged data quantity on internet can be calculated from the qty of transactions with an affine function"	ok
95	993	4.3.1.4. Test of model sensitivity to the quantity of data exchanges over the Internet	D	"These elements were determined using an average from the data collected from bakers"	Change in "This relation was determined using an simple average from the data collected from a few bakers"	ok
96	997	Table 19: Network traffic sensitivity analyses lower and upper bond in GB per year (2021)	D	Add in the table the values considered for the reference scenario		ok
97	997	Table 19: Network traffic sensitivity analyses lower and upper bond in GB per year (2021)	D	Check the values, it seems there are errors, not coherent with Table 13		corrected
98	997	Table 19: Network traffic sensitivity analyses lower and upper bond in GB per year (2021)	D	Add in the table the values for the average node (combination of public and private node)		added
99	1007	4.3.1.5 Test of model sensitivity to the share of public nodes	D	"The model is sensitive to the share of private and public nodes. In the default scenario, 62.5% of nodes are public nodes"	with data from table 5, this share is calculated as 1.35/2.11 = 64%, please correct	ok
100	1008-1009	4.3.1.5 Test of model sensitivity to the share of public nodes	T	"Private nodes are generating a lesser impact compared to public nodes because they are generating fewer data exchanges over the internet."	Remind in bracket the qty of data exchanged for a private node versus a public node and the % of reduction	ok
101	1009-1010	4.3.1.5 Test of model sensitivity to the share of public nodes	G	The range of reduction in impact for the first three environmental indicators	To be clearer, change by "The range of reduction in impact between a public and a private node for the first three environmental indicators	ok
102	1010-1011	4.3.1.5 Test of model sensitivity to the share of public nodes	G	"The mineral and metal resources use is stable between a public and private node."	Explain why	ok
103	1023	4.3.1.7. Test of model sensitivity to the transport hypotheses	T	Table 20: Test of model sensitivity to the transport hypotheses	No FU is mentioned. Please add it in the title of the graph or in the legend	Precised "default node" in the table.
104	1023	4.3.1.7. Test of model sensitivity to the transport hypotheses	G	There are small discrepancies between the numerical values for the reference scenario presented in this table and the values presented in Table 16 (eg fossil: 3130 MJ/node instead of 3132, particulate: 3.81E-05 disease inc instead of 3.82E-05, resource minerals: 8.66 g Sb instead of 8.65)	Align the values	ok
105	664	Table 8: Power for one node in different datacenter infrastructures	D	Very difficult to understand how the resulting power (W) is calculated	Please detail in bracket the calculation for each column (24.6 W =xxx)	ok
106	636	3.2.2.1. Baking equipment, Table 8: Baking equipment power (W)		Server (10% load) 224 Teads engineering and Spec power benchmark (see §2) of 3.2.2.3)	Remove the 10% in bracket for the server as 224 this is the total power of one server. Also not in line with the section saying that for the server (row 704), 14 W was considered	224 watt is the total power of one server under a 10% load
107	979	4.3.1.3 Test of model sensitivity to Internet Protocol network electrical intensity	G	This SA is run only of the 2021 year. However, the main difference between 2020 and 2021 for the Tezos blockchain is the number of transactions that increased by a factor 9. Total impact of the blockchain between 2020 and 2021 are presented in the report with some conclusions. It is then key to see how the assumption on the electricity usage of internet affects the 2021/2020 comparison as in the current model, this is the only part that varies with the number of transactions.	Calculate the results for 2020 with the higher electricity consumption per GB and present the results for each FU studied + total blockchain. Compare them with the 2021 series	ok
				The rest of the report was not reviewed as summary of SAs and conclusions may change after integrating the previous remarks		

LCA External review completed on the 25th of November 2021 by Hélène Lelièvre, Enviroconseil, Independent LCA consultant, third round		
Document reviewed: Study of the environmental impact of the Tezos blockchain, Life Cycle Assessment of the Tezos blockchain protocol, 24 November 2021 (all changed accepted)		

N°	line number	paragraph, figure, table	type (editorial, general, technical, data)	Comment	Recommandation	Answer
108	986		G	The SA asked (comment n°107) has not been run. The SA that has been run is also interesting, please keep it as it explores the uncertainty on another parameter used to calculate the energy linked to the Internet usage		ok
109	600	3.1.1. On the number of nodes on the Tezos blockchain	G	"Running for one week in May 2021, it recorded 935 public nodes (including bakers and others). Therefore, around 400 non-baker public nodes (wallets and other services) are not included in the study, and an unknown number of non-baker private nodes."	Explain what is a wallet or add it in the list of technical terms + refer to it in this section	ok
110	789	3.2.2.5. Internet use	G	"However, with a limited impact as with this estimation, the data exchanges of a private node represent between 0.5% and 2.5% of the one of a public node" : It is not clear how these values in bracket are coming from	Add in bracket "(% calculated with values from table 13)"	ok
111	791	3.2.2.5. Internet use	E	"A sensitivity analysis was performed on this parameter (see 4.4). "	Mention explicitely on "the data exchanged per public node" instead of "parameter"	ok
112	807	3.2.3. Electricity generation models	D	"The modules from Ecoinvent were used to "	Change by "from Ecoinvent 3.8"	ok
113	1005	table 19	G	513 not found, lower bound calculated as 389	Correct and rerun the SA if necessary	ok
114	1010	figure 16	G	comments on the graph should be corrected (eg between 13 % and 31% instead of 14% and 28% for CO2)	Put all the comments on the changes in the text directly and not on the graph, it will avoid to forget to udpate them when LCA results are updated	updated
115	1012	4.3.1.4. Test of model sensitivity to the quantity of data exchanges over the Internet	G	"the particulate matter emissions would increase by 13%. 15% read on the graph	Correct the value	ok

LCA External review completed on the 26th of November 2021 by Hélène Lelièvre, Enviroconseil, Independent LCA consultant, final check		
Document reviewed: Study of the environmental impact of the Tezos blockchain, Life Cycle Assessment of the Tezos blockchain protocol, 26 November 2021 (all changed accepted)		

N°	line number	paragraph, figure, table	type (editorial, general, technical, data)	Comment	Recommandation	Answer
116	173	executive summary	G	table 1 : resource use (minerals and metals) value for one node in 2020 (8.55 g Sb) is different from the value in table 19: 8.45 g Sb	correct value in table 19 ?	ok
117	175	executive summary	G	"With a similar number of bakers and a larger service offer, the impact of the Tezos blockchain for each transaction or gas unit consumed appears to lower"	Remove the part of the sentence dealing with gas unit as no comparative values between 2020 and 2021 are presented in the exe summary	ok
118	195	executive summary, Limits of the study, second	D	"Company estimated total public nodes to be 64% higher". This % is calculated as 68% (935/555-1, see table 5)	Correct the value	ok
119		Exe summary /2.2.1 Functional units/ Summary	G	As results are now also presented in the exe summary and summary section on the total blockchain, a sentence saying that the total impact of the Tezos blockchain is also calculated should be added. As only bakers nodes are included in the scope and knowing 68% higher public nodes were found by Nomadic Labs compared to the chain explorer (935 versus 555, table 5), I suggest for the title in the tables "For the total blockchain protocol (bakers nodes)"		One sentence added in FU 1) Running one node as a baker Changed title 4.2.2 And column label in table 18 (For the blockchain protocol (all baker nodes)
120	1080	4.3.8 Sensitivity analyses summary, Table 25: Sensitivity analyses summary in 2021	G	Vaues are not correct for the rows "private node", "public node" and "data exchanges -upper bound"	correct the % values in the table	corrected
121	1081	4.3.8 Sensitivity analyses summary	G	After table 16, can you put a copy of table 20 and table 23 (difficult to summarize more) or just a sentence refering to the 2 tables (this gives a different view on the uncertainty on the trend between the years)		Added after figure 10: trend of potential greenhouse effect between 2020 and 2021. Under the default scenario, the greenhouse effect increases by 3% for the blockchain protocol between 2020 and 2021 due to the change in activity. In the sensitivity analyses, alternatives hypothesis on the internet protocol network electrical intensity (4.3.3) and the quantity of data exchanged by the nodes (4.3.4) were tested. When taking into account the most conservative approaches in these sensitivity analyses the model becomes more sensitive to the number of transactions. With the high electrical intensity of the internet network hypothesis, the blockchain protocol greenhouse effect impact increases by 10% scenario, and when considering the upper bond of the data exchange hypothesis, it increases by 12%. The detailed results of the sensitive analyses for all the potential impacts can be seen in tables 20 and 23.
122	1021	1.1.1. Test of model sensitivity to Internet Protocol network electrical intensity	G	Table 20 should be introduced by a sentence saying that the goal of the analysis is to see the influence of the assumption of the comparison of 2020 and 2021 years		added
123	1105	5. Section V - Summary	G	2.44 E-7 g CO2e is not correct	change to 2.44 E-4 g CO2e	modified
124	1135	5. Section V - Summary	G	"When considering lower and upper bonds of the data collected on internet usage results can vary from -9% to +14%."	Values are found to be from -11% to +18% in the SA section (see table 15)	corrected

2. Annex 2: first critical review report

Critical Review Report of the PwC LCA of the Tezos Blockchain Protocol

Author: Hélène Lelièvre, independent LCA consultant, enviroconseil, France
Date: 2[nd] September 2021

1. Goal and scope of the critical review

This independent external review was carried out during June to beginning of September 2021. The LCA study on the Tezos blockchain protocol was carried out by PwC between February and June 2021 and was commissioned by Nomadic Labs who develops and maintains the Tezos blockchain protocol. The scope of the LCA study is only encompassing nodes run by bakers (the protocol) and not all blockchain nodes: nodes run by bakers and nodes run by other agents.

The external review was performed in a 4 steps process, on the following documents, transmitted by PwC:

- "Evaluation of the environmental impact of the Tezos blockchain, Life Cycle Assessment of the Tezos blockchain protocol", version of June 2021 (for the first round of comments),
- "Evaluation of the environmental impact of the Tezos blockchain, Life Cycle Assessment of the Tezos blockchain protocol", version of 13 July 2021 (for the second round of comments)
- "Evaluation of the environmental impact of the Tezos blockchain, Life Cycle Assessment of the Tezos blockchain protocol", final version of the report of 30 July 2021 (for the third round of comments).
- "Evaluation of the environmental impact of the Tezos blockchain, Life Cycle Assessment of the Tezos blockchain protocol", final version of the report of 31 August 2021 (final check).

In addition, 3 Webex between the reviewer and PwC team were organized to review by sampling the LCA modelling in the TEAM™ LCA software and the Excel file compiling the bakers interviews data. Additional calls were organized to discuss the versions of the report and some comments.

The goal of the critical review was to assess the compliance of the LCA study with ISO 14 040 and ISO 14 044 standards. It is mentioned that this LCA does not include a comparison of the Tezos blockchain protocol with other types of blockchains (no comparative assertion as defined by ISO 14 040).

2. Main findings and conclusions

Most of the reviewer comments were taken into account by the practitioner and the content of the report was improved. A few discrepancies between the input data and the data in the LCA model were detected but they were assessed by PwC as changing the LCA results at a maximum of 2%. The LCA results on the total blockchain were however recalculated to be consistent with one of the key input data which is the average number of nodes per baker. An additional sensitivity analysis asked by the reviewer was run on the quantity of exchanged data per public node. A global uncertainty analysis combining the key data uncertainties could not be run due to the technical limitations of the LCA tool. This would have allowed to better assess the global uncertainty of the LCA results, that is assessed to be higher than classical LCAs due to the structural variability of the data (data from the bakers' questionnaires, data on the equipment description and other literature data found on internet). Another remaining comment is concerning the conclusion that the impact of the blockchain for each transaction is lowering. It is assessed that it is difficult to have this assertion due to the fact that the correlation between the number of transactions and the quantity of exchanged data on the internet network (the latter being directly linked to the electricity consumption of the network) could not be determined. This limitation has been added by the practitioner in the report.

The LCA study is compliant with ISO 14 040 and ISO 14 044 requirements.

The other key findings of the LCA study review are as follows:

- The sections of the LCA report presenting the input data and assumptions were not enough developed and this was improved in the final version of the report, thus increasing the transparency of the study.
- The list of excluded steps was completed.
- The LCA model on the end-of-life part (end of life of equipment) is modelled in a simplified way (only the recovered part is taken into account, the rest being considered as landfilled but with no environmental impact associated with this destination). In reality, a fraction may be directly incinerated, leading to additional environmental impacts. For landfilling, in case environmental LCA impacts on soil, water or land use would be added in the scope, the LCA model should be improved.
- The third functional unit concerning running a smart contract was reformulated to be consistent.
- The quality of the data was better described by adding the assessment of the literature data used in the model.
- The scope of the study is only encompassing nodes run by bakers (the protocol), therefore the environmental impacts of the total Tezos blockchain peer-to-peer network per transaction and per gas unit is expected to be higher than the LCA results presented in the study due to nodes being run on the network by agents other than bakers. This limitation is listed in the report.

For a future study, the 3 following recommendations can be emitted:

- Update the electricity LCA models with updated background Ecoinvent models on fuel extraction and combustion as a bias may appear between processes using aggregated Ecoinvent data and processes using electricity flows;
- Refine the modelling of the equipment end of life;
- Use updated Life Cycle Impact Assessment methods like the PEF ones (Product Environmental Footprint, proposed by the European Commission), that have been consensually developed.

Detailed comments and answers of the first critical review

Remark: some minor editorial comments have been removed from the original list of comments. This is why the numbers of comments are sometimes not following each other

LCA External review completed on 1st July 2021 by Hélène Lelièvre, enviroconseil, Independent LCA consultant, first round

Document reviewed: Evaluation of the environmental impact of the Tezos blockchain, Life Cycle Assessment of the Tezos blockchain protocol, June 2021

N°	line number	paragraph, figure, table	Type (editorial, general, technical, data)	Comment	Recommendation	Answer of the practitioner
1	222	1.4. Glossary	E	Add XTZ in the glossary		done. Added Tez, and Tez has replaced XTZ in the report.
2	235	2.2.1. Functional units	T	Correct the sentence for the third FU as it is per unit of gas and not per smart contract		done
3	260	2.2.1. Functional units	T	Correct the formula for the third FU as the unit is impact per gas unit (S should be removed from the formula)		done
4	365	Figure 3: Tezos lifecycle	G	The life cycle stages are not structured the same way as the stages of the LCA results presented in section IV	Please structure the same way so it is clear what each stage includes	done ; modified both the figure and the table for more clarity
5	365	Figure 3: Tezos lifecycle	T	For the development phase, why not having included the life cycle of the laptop (embodied impact); It was done for other IT equipment and the data is available so it is inconsistent		For the development, the IT equipment is considered a capital good use for production. Therefore, it could be excluded based on LCI rules. In addition, it was not significant. See tab "results RC".
6	365	Figure 3: Tezos lifecycle	G	If production and end of life of developers laptop are still not included, add that in the "not included" part		done
7	398	2.3.2.2. List of excluded lifecycle stages	T	Packaging end of life is excluded arbitrary whereas the packaging description is available and LCA processes exist on this part.	Justify why	No data was available on the treatment of packaging (which route). It is distributed in many countries and by experience it does not carry a significant weight in life cycle assessment results.
8	398	2.3.2.2. List of excluded lifecycle stages	G	Add the landfilling of IT equipment (except laptop and computer) in the list of steps excluded and justify why		done
9	398	2.3.2.2. List of excluded lifecycle stages	T	Add the end of life of some parts of the equipment (eg end of life of rack, …) in the list of excluded steps		done
10	398	2.3.2.2. List of excluded lifecycle stages	T	Add the production and end of life of data center other equipment (cold generator, electricity generator…) than server in the list of excluded steps		done
11	398	2.3.2.2. List of excluded lifecycle stages	T	Add the production and end of life of developers laptop		done
12	457	Tableau 2 : Quality matrix	G	Add in the table the literature source (LCA model for the equipment production and end of life…) and qualify them on the same criteria		done
13	489	Table 2: Summary of information sources	G	Add for the row baker interview the description of the server in the cloud		done
14	533	3.2.2. Running nodes	T	Add the assumption that for all equipment a functioning 24h/24 h is considered with the same power (no idle or other phases)		done
15	535	Table 4: Devices use by bakers to run nodes	E	Heading should be share of baker (and not share of nodes)		done
16	536	3.2.2.1. Baking equipment	G	Add a sentence explaining what is a Raspberry Pi, Intel NUC, cloud virtual machine		done
17	537	3.2.2.1. Baking equipment	G	Add a sentence explaining what is a ledger nano S, cloud HSM		done
18	540	3.2.2.1. Baking equipment	G	Add a sentence saying what is considered as single board computer (referred to in the conclusions)		done
19	543	Table 6: Baking equipment power (W)	G	sources of power data are not mentioned	Add the sources used for the power of each equipment (add a column)	done
20	543	Table 6: Baking equipment power (W)	E	Replace computer by laptop as this is the terminology used before		done
21	543	Table 6: Baking equipment power (W)	T	Mention the source of 10% of load for the server		Added reference to the section on the topic
22	543	Table 6: Baking equipment power (W)	T	Add the Cloud HSM in the table		Done
23	545	3.2.2.1. Baking equipment	T	Add a sentence mentioning that the composition of equipment in materials + packaging is mainly based on assumptions (not real product description from manufacturers) except for laptop, computer…where the model is based on Ecoinvent models		done. Line 571
24	547	3.2.2.1. Baking equipment	T	Add a sentence stating the life duration is considered in general to be 5 years except for…		done

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25	582	3.2.2.3. Cloud computing and enterprise datacenter	T	Be more explicit about the source of 0.9 ratio (what was the topic of the PwC study quoted) + say explicitly that only 0.9 of router unit (router model used to model switch and firewall) was considered.		done
26	582-584	3.2.2.3. Cloud computing and enterprise datacenter	T	Add the fact that the all individual components of the network equipment were extrapolated by the same component, the router		done
27	609	2) IT equipment power consumption	T	Add a table displaying the power considered for each type of server		done
28	614	3) Other equipment embodied footprint	T	Data shown in the table 7 only allow to conclude on CO2e emissions only. The negligibility may be different for the abiotic depletion (see LCA results of blockchain where embodied impact is the main source)	Mention that the non significant aspect is only for CO2e	done
29	615	3) Other equipment embodied footprint	T	Mention the assumption taken on the number of server per node		included in 1) IT equipment embodied emissions
30	616	Table 7: Data center non-IT equipment carbon footprint	E	Footnote 9 is to be corrected, the link does not function		done
31	628	3.2.2.4. Nodes location	T	"The node location was collected by Nomadic Labs using a software"	Mention the year the data refer to and the period of data collection	done
32	634	3.2.2.4. Nodes location	T	Specify to what is applied the specific electricity mixes (baker equipment, data center..?). Specify also to what is applied the world mix		done
33	645	3.2.2.5. Internet use	T	"Nomadic Labs provided data on the network usage of one node over a one-month period,"	Mention if it was for a public or private node ? Or both	done
34	648	3.2.2.5. Internet use	T	Add "/ year" after the numbers of 510 and 4GB		done
35	648	3.2.2.5. Internet use	T	Add the min and max of GB/ node for both type to see the variability		done
36	684	3.2.4. Transport models	G	Transport step is described to occur for the upstream step and for the end of life of equipment but nothing is said about the latter step	Describe assumptions for transport occurring at the end of life of equipment	done
37	689	3.2.5. End of life modelling	T	Add the end of life fates considered for the IT equipment t, both for Europe and US and how both are averaged. Is there as fraction that is incinerated ?		Done, the plastic is incinerated.
38	695	3.2.5. End of life modelling	G	Add in the annex the Ecoinvent modules used to model the end of life of IT equipment and refer to this in the report.		Already in annex, reference added
39	695	3.2.5. End of life modelling	T	Add a sentence describing the type of modeling of end of life (cut-off , i.e. only impacts of treatment when recycled are considered with no avoided impacts)		done
40	695	3.2	G	Add a section describing the source of data for the number of transactions per year and the quantity of gas (what is presented in table 12)		done
41	701	3.3. Modelling and lifecycle inventory calculation tool	E	Mention the cut-off series after Ecoinvent version 3.7.1		done
42	708	4.1. Limits of the LCA study	T	"There are many applications build around the protocol which are not fully included in this study." Which applications are thus included? Which are not ?	Describe what is included and what is excluded	The application are not included, sentence was changed
43	709	4.1. Limits of the LCA study	G	"Therefore, the impact of the blockchain core protocol discussed in this study will decrease with wider adoption,"	Explain why it is not straightforward	the impact per service, sentence reworked
44	712	4.1. Limits of the LCA study	T	"The study only considers nodes of bakers, due to limitation in data availability for other nodes." Say explicitly which types of nodes are excluded		done
45	715	4.1. Limits of the LCA study	G	Mention the total number of bakers using Tezos blockchain to have an idea of the representativeness of the 70 answers by questionnaire		done

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46	719	4.1. Limits of the LCA study	G	"Some data was made available by bakers during the interviews." Describe the data obtained this way		done
48	727	4.1. Limits of the LCA study	G	Add the exact reference of "AFNOR study group on LCA."		No exact reference available. Uncertainties were discussed during a study group at the AFNOR in 2010.
49	742	4.2.1. Results for one node	T	"...;production, transport and end-of-life of internet access equipment."	List in a bracket the equipment considered	All the equipment is considered
50	745	4.2.1. Results for one node	G	"The baking equipment is the primary source" add after baker equipment (embodied or use)		done
51	747		G	"is the source of 71%"	Correct by 72%	done
52	748		G	62% of emissions	Correct by 63%	done
53	753	Figure 5: Environmental impact by indicator	T	The split of the total includes "security equipment" which has not been introduced in the split of stages end of page 29	Be consistent in the stage splitting or add a note explaining where these equipment are counted in the above results. Also, mention that on figure 3 of the life cycle	The equipment was included in baking equipment (it was mentioned) but added a note after the figure also.
54	758	Table 12: Key defining parameters of the blockchain in 2020 and 2021	T	Add the unit of gas in the table		Gas is a unit for smart contracts.
55	761	4.2.2. Results for the blockchain	G	Before table 13, add a sentence explaining how total of blockchain impact is obtained (value per node x number of node per baker x nber of baker)		done
56	760	4.2.2. Results for the blockchain	G	Add a sentence reminding the source of data for these parameters (TzStats for all except for number of bakers where it is from the questionnaires)		done
57	761	4.2.2. Results for the blockchain	G	mention for the first series of result "for all baker nodes"		done
58	765	4.2.2. Results for the blockchain	T	"the energy consumption by the consensus protocol of Tezos is not scaling with the increase in the number of transactions". The model is built this way, i.e. the number of GB exchanged per node is considered constant between years, whatever the number of transactions, which may be not the case. It is expected that the quantity of GB exchanged and the number of transactions are correlated. Thus, the impact of total transactions is the sum of a constant part and a variable part, function of the number of transactions.	Revise the mode of calculation per transaction considering the correlation between GB exchanged and number of transactions	Section 3.2.2.5 Internet Use Added "The network consumption is expected to vary depending on the number of transactions. However, the data given by bakers does not allow to estimate this correlation because the difference in data exchanges depending on the set-up (for instance system updates) were more influential to the total network activity of one equipment compared to the number of transactions. Only considering the validation of blocks would lead, according to Nomadic Labs, to a maximum theoretical usage of 512 kB per block multiplied by 1 block every minute, i.e. 269 GB / year. " Section 4.2.2. Results for the blockchain - Executive Summary and Conclusion With a similar number of bakers and a larger service offer, the impact of the blockchain for each transaction or gas unit consumed is lowering. Indeed, the energy consumption by the consensus protocol of Tezos is not increasing proportionally with the increase in the number of transactions.
59	771	4.2.3. Equipment environmental performance for running one node	T	Change "environmental performance in "CO_2e performance" as this section only focuses on CO_2e emissions		done
62	793	4.2.3. Equipment environmental performance for running one node	E	"Figure 7 includes embodied and use phase emission"	change by "embodied and use CO_2e emissions"	done
63	807	Table 14: Total blockchain protocol footprint in 2021 by development, private nodes and public nodes	T	Which parameters of the model differ between private and public nodes ? This should be reminded before presenting the results		done
64	807	Table 14: Total blockchain protocol footprint in 2021 by development, private nodes and public nodes	G	Which year was considered to calculate these results ?	Mention the year considered	in the table title. Added in column as well.
65	809	Table 15	G	It is not clear how results of table are calculated.	Add an explanation on how these results are obtained from the previous table	done
66	813		E	"In section 4.33.1.1"	Correct the number of the section	done
67	814-815		G	"These nodes are not run by bakers and therefore no data was collected on the equipment use or the practices (i.e. the uptime)."	mention then by who there are run	Not specific, every one that connect to the blockchain.
69	823		G	"They are included because there are believed to be of informative value."	It is not clear why they are of informative value. Can you explain ?	done
70	829	Figure 8: Model sensitivity to electricity mix	G	To what are corresponding the min and max of each scenario with a given grid ? It is not clear	Explain the min/max approach	The error bars represent the uncertainty range of the impact methods.
71	836		G	"gas emissions by 15% and 27% respectively"	correct 15% by 14%	done
72	848	4.4.1.3.	T	Remind that there is a factor of ten between the min and max		done
73	850	Figure 10:	G	Say why the indicator abiotic depletion potential (elements) is not presented in the results		done at the beginning of section 4.4
74	853	Figure 11:	G	Sentence in the graph should be revised with the right percentage (19% instead of 27%)		This is the correct number (comparison btw public and private not with default scenario)
75	853	Figure 11:	G	same remark as above on the absence of the abiotic (elements)		done at the beginning of section 4.4
76	859	4.4.1.4. Test of model sensitivity to the share of public nodes	G	Add the range of environmental reductions allowed by a shift from a public node to a private node		done
77	867	4.4.1.6. Test of model sensitivity to the transport hypotheses	E	"they consider that half of the equipment is transported by boat and half by sea."	Correct half by plane and half by boat	done
78	870	Table 17: Test of model sensitivity to the transport hypotheses	G	Abiotic (elements) is again lacking in the results that are presented		done
79	882	5. Section V - Conclusions	T	Revise the third FU expression (for one gas unit)		done

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80	889	5. Section V - Conclusions	G	"based on the data collected from bakers from mid-March to end-April 2021, from Tezos explorers, equipment constructors,"	Which data come from equipment constructors ? Not specified in the data description	Data on the weight of equipment / power consumption (router for instance). But this mention has been withdrawn from the conclusion because it is included in bibliographic literature (it does not come directly from the constructor but was found available online).
81	901	5. Section V - Conclusions	T	Precise which use phase is most impactful or the split between the baker equipment and the use of internet		done
82	1216	C.2.1. Assembly hypothesis	T	Mention the assumption that all the assembly steps of the equipment are considered in China		done
83	1221	C.2.2. Equipment model	T	Source of data for the electronics composition (and other parameters) is not mentioned	Add a column in the tables describing the sources of data or the assumptions	done
84	1221	C.2.2. Equipment model	D	Specify the nature of plastic in the tables		done
85	1231	C.2.2. Equipment model	D	Add one SSD on the second hand laptop composition		done
86	1232	C.2.2. Equipment model	D	Correct power of ledger: 0.135 W instead of 0.165 W		done
87	1235	Router / Network equipment	D	Explain before the table that the model considers the Ecoinvent model completed by an integrated circuit		done
88	1236	Router / Network equipment	D	Check the 0.071 kg value for PWB end of life (seen at 0.075 kg in Ecoinvent)		- 0.02 Integrated circuit memory type - 40% recycled 0.038 kg Corrected in report & model
89	872	4.4. Sensitivity analyses	T	An uncertainty analysis would be very interesting in order to combine the uncertainty of the key parameters: all explored in individual sensitivity analyses chapter (except the one on the electricity mix)+ uncertainty on the key data of quantity of GB exchanged per node (510 GB for public, 4 GB for private). This will allow to assess the overall uncertainty of the LCA results		This feature (Monte Carlo simulations) is not available in TEAM anymore. Added sensitivity to data exchanges.
90		TEAM model review	D	A small discrepancy exists in the number of nodes calculated with data from the questionnaires: number is calculated as 2.11 instead of 2.07 (due to the fact that the person who did the calculation did not exclude a baker with inconsistent data in the average). This is not considered as significant		Not significant for a node. However, results were updated for the blockchain / transaction and gas. This was important so that the results per node times the number of nodes per baker, times the number of baker matches the results.
91		TEAM model review	D	Quantity of computer per server is 4 units for the data center server whereas the ratio is 3.6 in the servers used in the other configurations	Correct and assess the impact on the total results	Not significant
92		TEAM model review	D	Quantity of SSD per server is 4 instead of 16	Correct and assess the impact on the total results	Not significant
93		TEAM model review	D	Quantity of GB per private node is 510 GB instead of 540 GB in the report	Correct and assess the impact on the total results	Not significant
94		TEAM model review	D	Quantity of electricity for the ledger production has been forgotten. It is not considered as significant	Correct and assess the impact on the total results	Not significant

LCA External review completed on 28th July 2021 by Hélène Lelièvre, enviroconseil, Independent LCA consultant, second round

Document reviewed: Evaluation of the environmental impact of the Tezos blockchain, Life Cycle Assessment of the Tezos blockchain protocol, 13 July 2021

N°	line number	paragraph, figure, table		Type (editorial, general, technical, data)	Comment	Recommendation	Answer of the practitioner
95	6			E	Update the date of the report (first page and footer)		done
96	154	Limits of the study (in the exe et conclusions)		G	Add an additional limit concerning the model for the total blockchain: -it was not possible to characterize the correlation between the size of the data exchanged per node (directly defining the energy consumed by the internet network) and the number of transactions per node and a constant value of exchanged volume was considered -for the impact of the total blockchain, only bakers nodes were considered and not total public nodes (that are found to be 70% higher by a Nomadic Labs measure)		1) Added 2) Already in the limits, added the 70% figure.
97	391			E	"that amy both be deemed as the canonical chain." : correct by any ?		corrected
98	417	Figure 3		G	Rename the stages the same way as how the LCA results are split	baker equipment instead of " IT equipment operating on the chain" or "devices"	done
99	514		2.5	E	"in section 193" : replace 193 by the right number of section		done
100	515	Table 2: Quality matrix		T	The time coverage for Ecoinvent processes is not 2020 as data are much older. Based on what is presented in the annexes, it is 1998-2020		corrected
101	527	2.6. Critical review		E	"The comments made by the representatives " : replace representatives by LCA expert		done
102	549	Table 2: Summary of information sources		G	Add in the section "LCI databases and bibliography" other key data found on the web: eg electricity ratio for internet, consumption of a node in a datacenter, conso shared cloud, life time duration of equipment...		done
103	624	3.2.2.1. Baking equipment		G	"For the study, the assumption is made that equipment are running 24 hours a day for the whole year". Add the information that the Tezos protocol requires a validation of block each minute, thus requiring that the equipment is functioning 24/24h		It is not the case, the equipment could be turned off and on based on its baking calendar, but it would need some time to synchronize with what happened on the chain in the meantime. However, based on our itw and questionnaire baker do not generally turn off their equipment. However, as discussed the baking calendar does not affect the consumption of a node, we added in the report the following explanation: The solicitation of the device running a node is mostly stable with one block to integrate and broadcast every minute, the action of the baker for that block (endorsing, validating or just broadcasting) is not expected to significantly influence power consumption. A peak in computing power needs occurs at the end of a cycle that happens roughly every 68 hours.
104	595	Table 4		E	In the heading, "Share of nodes" should be replaced by "share of bakers"		This is indeed the share of nodes. One baker can have several equipment in different categories or several nodes in the same category, therefore the share of baker would be slightly different.
105	758			G	"multiplied by 1 block every minute" Add in bracket that this frequency is part of the Tezos Protocol		done
106	806			T	Mention the 2 values of recycling rates for Europe and US and how the average was calculated (simple average ?)		42% for EU and 40% for US added.
107	808			E	"and the plastic is incineration" replace by incinerated		done
108	812			E	"to go to a landfilled" : replace by landfill		done
109	859			E	"This figure illustrates the weight the embodied greenhouse " correct by "the weight of the embodied"		done
110	898			G	"These nodes are not run by bakers " Mention then by who they are run. It is unclear the differences between these nodes and the nodes counted by the chain explorer		done
111	940			E	"public nodes account for 68% of the greenhouse effect with only 63% of nodes". 68% should be corrected in 70%		done
112	950			E	"The table can be read as follow: "one public node emits on average 187 kg CO_2 eq" 187 kg should be corrected in 186 kg		done
113	971			E	"abiotic depletion potential for element " correct by "of elements"		done
114	1004			G	"and considering the data exchanges " change by "and considering also the data exchanges " for a better clarity		This section was modified completely
115	1006			G	"In the sensitivity analysis, the lower and upper value of data exchanges collected from baker are considered"	mention in bracket the min and max values considered	done
116	1082			G	" A private node has around 25% lower impacts compared to a public node (except for element depletion)." add "for which there is no change" after "element depletion"		done

LCA External review completed on 27th August 2021 by Hélène Lelièvre, enviroconseil, Independent LCA consultant, last round of comments						
Document reviewed: Evaluation of the environmental impact of the Tezos blockchain, Life Cycle Assessment of the Tezos blockchain protocol, 30 July 2021						

N°	line number	paragraph, figure, table	Type (editorial, general, technical, data)	Comment	Recommendation	Answer of the practitioner
124	591	3.2.1 Baking equipment	D	"3 years" : add "(assumption)" after 3 years to be transparent on the source of the data		done
131	991	table 20		value of ADP element: there is a unit error. The value should be multiplied by 1000. For the other values, use the same scientific notation of numerical values than in the table presented in the exe summary and section § 4.2.1	correct the table	done
132	991	table 20		There was an inversion of results values between the low and high network intensity values	correct the table	done
133	1007	5. Section V - Conclusions		"impacts" : to be remplaced par LCA impacts		done
134	713-118	3.2.5 Internet use		This section is not clear enough on how the average value of 510 GB/year was calculated.	Please reformulate, adding sources and information on the calculation procedure.	This was reformulated
135	848-850	4.2.2 Results for the blockchain		"The value for data exchanges considered for the two periods does not change because this information was collected over one different time frames with different bakers and a correlation between the number of transactions and data exchanges could not be determined. "	Reformulate/correct as it is not clear enough.	This was reformulated