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Review

Towards an ITU Standard for DLT Energy Consumption

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Abstract: The emergence of Distributed Ledger Technologies (DLT) in the past decade has challenged our imagination to discover new, innovative and disruptive solutions to problems in domains ranging from finance and healthcare to supply chain and Smart Cities. However, the enormous energy consumption that has been observed in some of the most successful DLT applications raises the question of their long term sustainability. This article reviews the standardization efforts of the International Telecommunications Union (ITU) to provide guidelines to regulators and policy makers for making informed decisions on the applicability and sustainability of DLT architectures from the point of view of energy consumption.

Keywords: blockchain; distributed ledger; energy consumption; standardization; policy making

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1. Introduction

Distributed Ledger Technologies (DLT) have been a source of innovation, disruption and criticism since their appearance more than ten years ago. They are the subject of research both in Academia and Industry and are becoming increasingly accessible to citizens all over the world. As innovative ways of using this technology are constantly being discovered, they are often in the spotlight of news and media either for their desired effects or their undesired side-effects.

Energy consumption is one of the undesired side-effects of the DLT paradigm. It has been heavily criticized and has become one of the major concerns regarding the sustainability of DLT applications, particularly in the domain of Decentralized Finance (DeFi). The energy consumption of some of the most successful deployments of DLT is comparable to that of whole countries [1,2]. The research in and adoption of DLT applications in an increasing number of domains outside DeFi make the analysis and understanding of the reasons behind the energy consumption of DLT even more significant [3]. This has led to extensive examination and scrutiny from researchers, regulators and policy makers in regards to the impact this technology has on the environment and whether or not it can be sustainable in the long term [4].

At the same time, there have been numerous initiatives in standardization organizations, including International Organization for Standardization (ISO), Organisation for Economic Co-operation and Development (OECD) and International Telecommunication Union (ITU), to identify and formalize the building blocks and characteristics of this emerging technology, in order to publish guidelines and standards that policy makers and regulators can use to make informed decisions on when, how and at what cost DLT can be deployed.

This article reviews the activities that took place in ITU in regards to the standardization of DLT with particular focus on its energy consumption. These include the research being done in understanding the reasons behind the enormous energy consumption of a subset of the available DLT technologies, its relationship with the energy efficiency of the equipment used and the creation of guidelines for regulators and policy makers to enable them to balance the positive and negative aspects of this technology.

The article structured is as follows: the next section starts with an introduction to ITU, its mission, governance and working practices for studying new and emergent technologies, followed by an overview of the standardisation activities targeted specifically to DLT. In the Discussion section, the key DLT concepts needed to understand its relationship with energy consumption are introduced and the ITU findings regarding the DLT energy consumption are presented in detail. The article concludes with a summary of the guidelines from the ITU in regards to the DLT energy consumption and the evolution of the ITU standardization activities in the DLT domain.

2. Relevant Sections

The International Telecommunication Union (ITU) is the United Nations' specialized agency for Information and Communication Technologies (ICT). It was founded in 1865 to facilitate international connectivity in communications networks and among other activities, it develops the technical standards that ensure networks and technologies seamlessly interconnect [5]. ITU is active in three main sectors:

- Radiocommunication Sector (ITU-R) which coordinates the vast and growing range of radiocommunication services, as well as the international management of the radio-frequency spectrum and satellite orbits [6].
- Telecommunication Standardization Sector (ITU-T) which produces ITU Standards, also known as Recommendations, that enable ICT systems to work and interoperate seamlessly [7].
- Telecommunication Development Sector (ITU-D) which is focusing on creating an enabling environment for ICT development and fostering the development of telecommunication and ICT networks to better serve the world's Least Developed Countries and marginalized communities everywhere [8].

The standardization of DLT technologies falls in the scope of ITU-T, which among other things, is responsible for producing studies on methodologies for evaluating ICT effects on climate change and publishing guidelines for using ICTs in an eco-friendly way. The Standards published by ITU-T, also known as ITU-T Recommendations, are developed within Study Groups (SG) that are created ad hoc for each area of interest and assemble experts from around the world. ITU-T is using a contribution-led, consensus-based approach to standards development in which all countries and companies, no matter how large or small, are afforded equal rights to influence the development of ITU-T Recommendations [9].

When an ITU-T Study Group needs to analyse a particular emerging technology that is not covered by the current body of knowledge, it can establish a targeted Focus Group. The ITU Focus Groups provide an alternative working environment for the quick development of specifications in a specific area. The key difference between Study Groups and Focus Groups is the freedom that the latter have to self-organize, freely choose their working methods, leadership and types of deliverables [10].

2.1. The ITU-T Focus Group on Data Processing and Management to Support IoT and Smart Cities & Communities (2017–2019)

In March 2017 the ITU Telecommunication Standardization Advisory Group established a focus group in order to conduct research, identify and study characteristics of effective Smart Cities & Communities (SC&C) data management systems, analytics and emerging trends including blockchain related to Internet of Things (IoT). This Focus Group completed its work in 2019 and produced a series of Technical Reports and Specifications covering numerous aspects of the DLT domain [11]. The DLT related deliverables of FG DPM are summarized in Table 1.

Table 1. FG DPM - DLT related deliverables.

Type	Title	Description	Reference
Technical Report	Overview of blockchain for supporting IoT and SC&C in DPM aspects	Provides an overview of blockchain aspects related to data processing and management (DPM) for IoT and SC&C	[12]
Technical Specification	Blockchain-based data exchange and sharing for supporting IoT and SC&C	Specifies the requirements, functional models, platform and deployment modes of blockchain-based data exchange and sharing for supporting IoT and SC&C	[13]
Technical Specification	Blockchain-based data management for supporting IoT and SC&C	Specifies the requirements, functional models, platform and deployment modes of blockchain-based data exchange and sharing for supporting IoT and SC&C	[14]
Technical Specification	Identity framework in blockchain to support DPM for IoT and SC&C	Provides support for designing, developing, integrating an identity framework in blockchain to support aspects of data processing and management for IoT and SC&C.	[15]

2.2. The ITU-T Focus Group on Application of Distributed Ledger Technology (2017–2019)

In May 2017 the ITU Telecommunication Standardization Advisory Group established the first Focus Group specifically for DLT technologies. This Focus Group completed their work in 2019 and produced a series of Technical Reports and Specifications covering numerous aspects of the DLT domain [16]. The deliverables of FG DLT are summarized in Table 2.

Table 2. FG DLT deliverables.

Type	Title	Description	Reference
Technical Specification	DLT terms and definitions	DLT terms and definitions containing a baseline set of definitions of terms commonly used in the context of DLT	[17]
Technical Report	DLT overview, concepts, ecosystem	Overview, key concepts and description of the DLT ecosystem	[18]
Technical Report	DLT standardization landscape	Description of DLT standardization landscape as of July 2019	[19]
Technical Report	DLT use cases	Consolidation each of the real-world use cases gathered during the lifetime of FG DLT, also presenting the knowledge extracted from these use cases interms of DLT competitive advantage, main barriers to DLT adoption and standardization benefits	[20]
Technical Specification	DLT reference architecture	DLT reference architecture specifying the hierarchical relationship, specific functions and core components of the architecture	[21]
Technical Specification	Assessment criteria for DLT platforms	Definition of an assessment framework for DLT platforms, including a set of criteria for functionality, performance and other aspects.	[22]
Technical Report	DLT regulatory framework	DLT regulatory framework which brings into focus the topics that are of concern to regulators and supplies practical recommendations for users, regulators, and technologists	[23]
Technical Report	Outlook on DLTs	Explores the technological and societal trends in the field of DLT	[24]

2.3. The ITU-T Focus Group on "Environmental Efficiency for Artificial Intelligence and Other Emerging Technologies" (FG-AI4EE)—(2019–2022)

In 2019 the ITU-T Study Group 5-Environment and circular economy established a Focus Group for "Environmental Efficiency for Artificial Intelligence and other Emerging Technologies" (FG-AI4EE) with the mandate to:

> *identify the standardization needs to develop a sustainable approach to AI and other emerging technologies including automation, augmented reality, virtual reality, extended reality, smart manufacturing, industry 5.0, cloud/edge computing, nanotechnology, 5G* [25].

Participants in FG-AI4EE were individuals with either scientific or practical background who are recognised in their domain and were either representatives of ITU-members or members of the Academia. They joined the Focus Group voluntary and participated in meetings that took place either in physical or in virtual form. The Focus Group was organized in Working Groups (WG), which were assigned to designated leaders by ITU. The FG-AI4EE's Working Groups structure was as follows:

- Working Group 1: Requirements of AI and other Emerging Technologies to Ensure Environmental Efficiency
- Working Group 2: Assessment and Measurement of the Environmental Efficiency of AI and Emerging Technologies
- Working Group 3: Implementation Guidelines of AI and Emerging Technologies for Environmental Efficiency

The FG-AI4EE kicked-off its activities in Vienna in December 2019 with 56 expert members from all over the world. During the first, plenary Focus Group's meeting, the participants submitted proposals for the development of specific documents that would address the topic and context of each of the Working Groups. In the plenary meeting lead by the WG leaders, the participants presented the justification of their proposals which were then put into voting in order to decide on their acceptance, revision or rejection. The accepted proposals were labeled "working items" or "deliverables" and the experts that submitted them were assigned the role of the editor of each deliverable.

Each WG agreed on a plan, with regular meetings that coordinated and monitored the progress of the deliverables. During the meetings, which were chaired by the WG leaders, the editors presented the progress of their work, while the experts contributed with comments and suggestions for further development. When a deliverable was completed, a dedicated meeting was held where participants verified its completion and decided on its acceptance. Upon acceptance, the deliverable was registered in the ITU library as an official document and could then further evolve to a standard under an ITU Study Group.

It should not come as a surprise that DLT was identified among the emerging technologies to have a significant effect on the environment and that there were open questions regarding its sustainability. In order to address these concerns, Working Group 2 of FG-AI4EE decided to work on a Technical Specification for providing Guidelines on Energy Efficient Blockchain Systems.

Due to the pandemic situation from 2020 through 2021, all the work of Working Group 2 was performed exclusively using Virtual Meetings. The content and key areas of the Technical Specification were drafted and reviewed by the Focus Group in February 2020. The team worked on the specification and presented the progress of the work in 6 Virtual meetings held roughly every two months from February 2020 through January 2021. In March 2021 the first draft version was sent to the Focus Group for comments which were addressed by April 2021 when the Technical Specification was circulated to an audience of 300 experts for further review. The FG-AI4EE completed its work in December 2022. The accepted deliverables of Working Group 2 of the Focus Group are available at [26]. With the conclusion of the FG-AI4EE activities, the Guidelines on Energy Efficient Blockchain Systems was released as a Technical Specification (Table 3).

Table 3. FG AI4EE - DLT related deliverables.

Type	Title	Description	Reference
Technical Specification	Guidelines on Energy Efficient Blockchain Systems	DLT energy demands, optimization and efficiency	[27]

3. Discussion

Although the available DLT architectures and implementations vary greatly, the key finding of the "Guidelines on Energy Efficient Blockchain Systems" Technical Specification is that the relationship between DLT and energy consumption is technology-agnostic. More specifically:

> *the energy consumption of a DLT is negatively correlated with the level of trust we place on the operator of the DLT; as trust decreases, energy consumption increases* [27].

In the following section the justification of this statement is presented in detail.

3.1. DLT High Level Architecture

The DLT High Level Architecture is discussed extensively in [21]. In Figure 1 the key components of a DLT solution are presented. The consensus algorithm is the "heart" of a DLT and is the key ingredient that makes it stand out from all other data storage technologies. As we will see in subsequent sections, the choice of the consensus algorithm has the greatest impact in the DLT energy consumption.

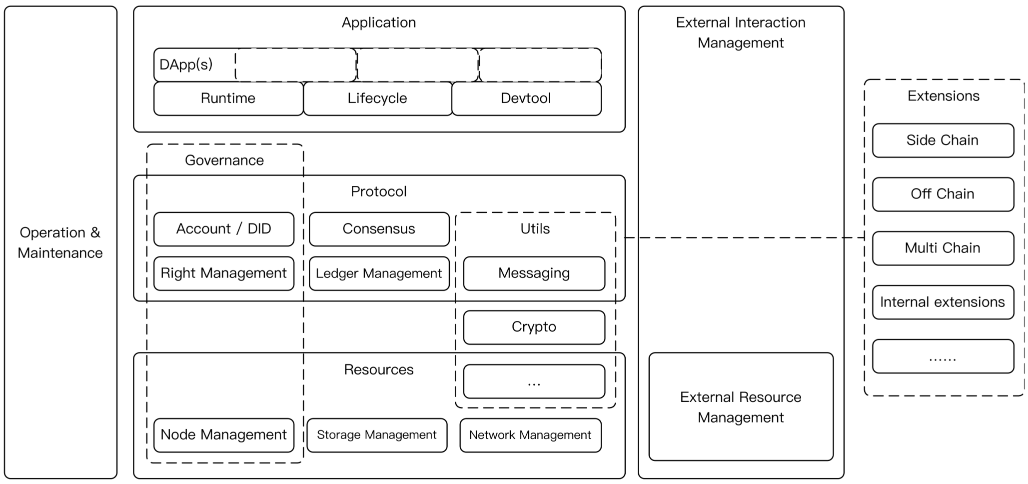

Figure 1. High-level conceptual architecture of DLT [21].

Consensus algorithm aside, one may argue that all other layers and components of the DLT HLA in Figure 1 can be implemented one way or another using traditional software engineering and database technologies in a much more energy efficient way. However, the common denominator across any non-DLT implementation is that it requires a central authority guarding the "state" of the system. "State" can be for example the immutability of a record in a database, the role and permissions of the users or the business logic that an application is executing. This central authority is responsible for resolving any disputes regarding the proper state of the system and has the power to modify it as needed. For this reason, it is standard practice in traditional data storage systems to define governance rules that specify when, how and to what extent the central authority can exercise its power.

DLT has disrupted this approach by introducing a mechanism that can ensure system consistency, agreement on the system state, immutability and transparency by design without a central authority and even without the need for human intervention. This mechanism is commonly referred to as "consensus algorithm" and, at its core, it provides

> "*. . . a single opinion of what happened, when it happened and what should happen because of it. . .*" [28]

3.2. The Three Paradigms of Consensus

There are three primary paradigms for reaching consensus in a DLT system, the Proof of Work, the Proof of Stake and the Proof of Authority. We will review them briefly in the following sections.

3.2.1. Proof of Work (PoW)

This is the algorithm that was invented to power the Bitcoin DLT and was first described in the Bitcoin whitepaper [29]. There are numerous sources, books and journals that describe the algorithm in detail, indicatively [30,31]. In [27] a simplified version of a PoW consensus algorithm is presented and the core concepts are introduced in a non-technical fashion to allow even non-DLT experts to understand the core concepts and design decisions behind PoW. The PoW consensus algorithm has several desired properties that allow:

- permissionless access to the DLT
- no single point of failure
- resistance to attacks by malicious actors
- decentralization

At the same time, this algorithm has several drawbacks, of which one really stands out; in order to achieve the above properties at scale, a valuable physical resource needs to be spent in order to secure the data stored on the DLT. The expenditure of the selected valuable physical resource is at the core of this mechanism as this expenditure is used to secure the DLT by making the cost of attacking it proportional to cost of the physical resource being spent.

In the case of Bitcoin-type DLTs [29,32] this valuable resource is electrical energy, but this is not a strict requirement. In the case of Chia [33] for example the valuable resource is disk space. Although at this time the discussion of the DLT sustainability is focused on the electrical energy consumption, primarily due to the success of the cryptocurrencies which use a Bitcoin-type PoW consensus algorithm, it can be expected that if a PoW paradigm that uses valuable resources other than electrical energy have similar success, sooner or later the discussion of the consumption of these resources will start [34].

3.2.2. Proof of Stake (PoS)

The PoS consensus algorithm has been invented to address primarily the high energy consumption of PoW. While maintaining most of the PoW desired properties, it introduces a mechanism for securing the data stored on the DLT that relies on economic incentives rather than the cost of energy consumed.

At a high level, this mechanism controls which nodes can have the permission to write data to the DLT by requiring each of them to commit a deposit of significant value, also known as "stake", which they will lose if they violate the rules of the PoS consensus algorithm. This approach reduces the needs of energy consumption by several orders of magnitude.

Etherium is one of the most successful DLTs that use PoS. It was created in 2013 using the PoW consensus algorithm [35] but switched to PoS in 2022 [36,37]. The effects of this change were far fetching and affected the evolution of Etherium in controversial ways. However, the effect the change to PoS had on the energy consumption is undisputed. The moment the change was deployed the Etherium DLT energy consumption fell almost instantly by 99.98% [38–40].

3.2.3. Proof of Authority (PoA)

The PoA consensus algorithm controls even more strictly which nodes have the permission to write data to the DLT by explicitly appointing those nodes. This mechanism presupposes the existence and acceptance of a central authority that decides which nodes are selected and allowed to participate in the DLT operation. This approach reduces even further the energy consumption and can lead to deployments with energy use comparable to traditional ICT architectures. A notable class of DLTs using PoA with a wide choice of consensus algorithms are the ones developed by the Hyper Ledger Foundation [41,42].

3.3. Smart Contracts

One additional aspect of the DLT technologies that stands out in terms of energy consumption is the support for Smart Contracts [22,43]. A Smart Contract is essentially a user defined software application that is stored on the DLT and may be invoked on request. When invoked, each node of the DLT network executes the code of this application as part of the consensus mechanism. Not all DLTs support Smart Contracts; the Etherium DLT for example supports them, the Bitcoin DLT does not. The support of Smart Contracts is also orthogonal to the consensus algorithm; PoW, PoS and PoA DLTs can support Smart Contracts. From the energy consumption perspective however, all other things being equal, a DLT that supports a Smart Contract mechanism consumes more energy than one that does not.

Depending on the software application's complexity a Smart Contract may have an exponential impact on the energy consumption of the blockchain as the number of nodes increases. For this reason, the design of the DLTs that support this functionality have control mechanisms in place to avoid abuse of Smart Contracts by malicious users. In Etherium for example, each code operation that a Smart Contract executes carries a cost which the user that requested its execution needs to pay. If the user does not have adequate funds, the Smart Contract execution is halted. As the complexity of the application increases, so does the cost of executing it. This mechanism ensures that highly complex Smart Contracts will not be invoked on the DLT as their execution will be prohibitively expensive.

3.4. The Relationship of DLT Technologies and Energy Consumption

From the discussion so far we can establish that there is a relationship between energy consumption and centralization. In [44] a comparison of the estimated energy consumption among different blockchain architectures is presented with an emphasis on the selection of the consensus algorithm. As described above, the choice of the consensus algorithm has the greatest impact on the total energy consumption. In fact, as the consensus algorithm becomes more "centralised" the total energy consumption approaches that of a traditional ICT architecture. There is, therefore, a positive correlation between the consumption of the physical resource and the autonomy of the DLT which is enforced by the consensus algorithm. As the autonomy increases, so does the consumption as is also discussed in [44] where a comparison of typical blockchain architectures is presented. This relationship is graphically presented in Figure 2.

From the brief description of the PoW consensus mechanism it is apparent that among the three families of consensus paradigms, PoW has the highest energy consumption. For this reason, we will now focus on the this consensus algorithm and explore the relationship between energy consumption, equipment efficiency and the value of the assets stored on the DLT.

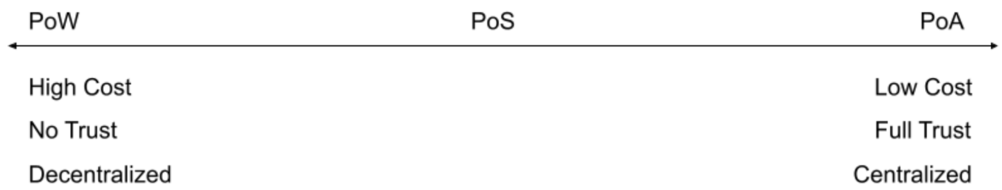

Figure 2. Consensus algorithm impact on DLT operation.

3.4.1. PoW DLT Energy Consumption

The dynamics of the energy consumption of PoW blockchains with particular focus on Bitcoin have been discussed extensively in the literature, indicatively [4,45–48].

The calculation of the exact energy consumption of a PoW DLT is not a straightforward task due to its decentralized and open nature [49]. Various approaches have been proposed but the general strategy is rather common. First, a lower and upper bound of the consumption is calculated and then an estimate between these two extremes is calculated using a heuristic algorithm [44].

The lower bound is calculated by assuming that the members of the network use equipment that is as close to the optimum efficiency as realistically possible.

The upper bound is calculated by assuming that the members of the network operate in an economically rational way and their earnings from the liquidation of the rewards received by the PoW algorithm as assets stored on-chain (e.g., the Bitcoins received as rewards in the case of the Bitcoin DLT) are at least equal to the capital and operational cost of their equipment.

If the total cost of participating in the DLT is lower than the expected profits, more members will join, moving the total energy consumption up. If the cost is higher than the expected profits, the less efficient members will eventually leave the DLT, moving the total energy consumption down.

As an example, the Bitcoin DLT estimated power and annualized energy consumption at the time of writing according to Cambridge Bitcoin Electricity Consumption Index (CBECI) [1] and Digiconomist Bitcoin Energy Consumption Index [2] are summarized in Table 4.

Table 4. Bitcoin DLT estimated power and annualized energy consumption.

	Power (GW)	**Annualized Energy Consumption (TWh)**
Cambridge Bitcoin Electricity Consumption Index	20.08	176.02
Digiconomist Bitcoin Energy Consumption Index	17.83	156.22

In order to fathom the energy consumption of the Bitcoin DLT it is customary to compare it with the estimated energy consumption of whole countries. At the time of writing, both [1,2] agree that the Bitcoin's DLT energy consumption is between that of Poland and Thailand. However, as [1] points out

> *[. . .] Comparisons tend to be subjective—one can make a number appear small or large depending on what it is compared to. Without additional context, unsuspecting readers may be drawn to a specific conclusion that either understates or overstates the real magnitude and scale. [. . .]*

Without going into the presenter bias in detail, it is worth mentioning that [1] makes the point that the Bitcoin DLT energy consumption could also be compared with the energy consumption of modern cities as

> *[. . .] certain cities or metropolitan areas in developed countries are operating at similar levels [. . .]*

As a final example, the Transport and Distribution loses of the US power grid alone could power the Bitcoin DLT 1.2 times [1].

A detailed analysis of the model and parameters used to calculate the CBECI index is available at [50] which is aligned with the high level steps presented in [44] and can be used as reference to expand and improve on the PoW energy consumption estimation calculations.

3.4.2. Equipment Energy Efficiency

Although it seems counter-intuitive at first, the energy efficiency of the equipment used in a PoW DLT does not affect in the long term its energy consumption. In fact, this is a property that actually makes the PoW consensus algorithm so powerful.

Let us assume that all the equipment used in a PoW DLT gained a 50% efficiency increase. This will allow the production of the same results by spending half the energy that was spent before, which will lead to a drop of the total energy consumption by 50%. Assuming that the value of the assets stored on-chain remains constant, the value of the energy-not-spent becomes an additional source of profit for the operators of the DLT. Due to the competitive nature of the PoW consensus algorithm, the members of the network have a couple of strategies to explore.

If they are honest members, they may decide to invest part of their profits to additional equipment in order to be able to receive a larger amount of the operational rewards from the DLT PoW algorithm and continue to do so as long as they remain profitable (see for example [30] for a detailed analysis of how PoW distributes rewards to the operators of a DLT). If all members behave in an economically rational way and follow this strategy, this will lead to a constant increase of the total computing capacity of the network. The PoW consensus algorithm will kick in automatically and increase its difficulty in order to ensure the stability of the system which will lead to more energy being spent in order to produce a new block on the DLT. This will eventually converge to a new stable equilibrium, where the DLT consumes the same amount of energy as before the introduction of the efficient equipment because now the equipment needs to work longer to produce the same results and keep the perceived value of the assets stored on-chain at the same levels.

If the members are dishonest, they will try to exploit the increase in efficiency by using the more efficient equipment to launch a 51% attack on the DLT and "out-work" the honest nodes by operating in parallel with them in order to produce a different version of the DLT that contains altered stored assets in a way that is profitable for them, for example by double spending tokens (see [30] for a detailed analysis of a 51% attack). The dishonest nodes need to spend at least the same amount of energy needed to control the 51% of the total DLT compute capacity. In this case the network will also eventually consume again an amount of energy at the same order of magnitude as before the introduction of the more efficient equipment. However, by the time this happens the trust on the DLT will have collapsed and the value of the assets stored on-chain will drop to zero.

To summarize, in a PoW DLT the total energy consumption will converge to an amount of value proportional to the value of the assets stored on the DLT regardless of the equipment efficiency.

3.4.3. The Cost of Trust

> *"Blockchain solves the issue of multiparty contention without having to involve a human"* . [28]

A different perspective on the DLT energy consumption is to think about it in terms of the cost the members of the blockchain are willing to pay in order to not trust anyone, not even each other.

A PoW DLT provides a way to have complete autonomy without a central authority. The cost of securing this system from internal and external attacks is translated via the PoW consensus algorithm to the consumption of the valuable physical resource and is proportional to the perceived value of the assets stored on-chain.

In a PoS, PoA or non-DLT architecture, we reduce or even eliminate this cost by consenting to gradually higher levels of centralization and control. The reduction of the valuable physical resource consumption comes at the expense of the trust we are placing to the various levels of authority introduced.

Taking again Bitcoin as an example, the market capitalization or, in other words, the total perceived value of the assets stored on the Bitcoin DLT on 25 March 2024, 16:45:42 UTC was in the order of $1.378 trillion [51]. Technically, the whole Bitcoin DLT can operate with a much smaller number of nodes because the PoW consensus algorithm automatically adjusts its "difficulty" to match the available compute capacity of the DLT. As the capacity decreases, the PoW difficulty also decreases proportionally in order to achieve the configured desired rate of block creation (one block every 10 min on average for the Bitcoin DLT). This has been observed in practice with the drop of the Bitcoin network difficulty due to the changes in the balance of the network nodes when in May 2021 China banned Bitcoin mining in its territory [52–54]. At the limit, this may go to as low as a single node making all the computational work needed for the PoW consensus algorithm. However, instead of trusting a single operator with the single node to operate the whole Bitcoin blockchain, a huge network has emerged organically that does essentially the same thing with the key difference that the node operators and the blockchain users do not trust anyone.

Ignoring the capital costs of the equipment and the labor to set up the network, how much does it cost per day in electricity alone to operate the Bitcoin, a DLT with a value of $1.378 trillion? In Table 5 we can see a back-of-the-envelope calculation based on the price data from [51] and the estimated power requirements from [1] at the time of writing.

Table 5. Bitcoin DLT estimated daily electricity cost.

Price of BTC (25 March 2024 17:00 UTC), [51]	$70,259.59
Market capitalization (25 March 2024 17:00 UTC), [51]	$1,380,737,970,155
Estimated range of the Bitcoin DLT power, [1]	9.93–59.00 GW
Estimated daily electricity cost of the Bitcoin DLT assuming an average price of electricity of 0.05 $/KWh, [1]	$11,926,000–$70,800,000

From this perspective, the cost of operating a PoW DLT can be interpreted as the cost of our lack-of-trust.

3.4.4. Energy Consumption as a Security Mechanism

In Section 3.4 we made the point that a decrease in energy consumption of a DLT increases the "centralization" of the system. The opposite is also true; as the energy consumption increases, the cost of modifying the data stored on the DLT becomes prohibitively high. The PoW consensus algorithm is by-design energy consuming so that in theory its members can trust the system without trusting each other. This has been verified in practice in the Bitcoin DLT, however there are signs that energy consumption alone cannot guarantee the security of a DLT.

The cost of participating in the Bitcoin DLT has been in an almost constant increase from the time of its creation, mirroring the overall price increase of Bitcoin. It is currently practically impossible to participate in the Bitcoin DLT as a single member because the probability of receiving a reward from the operation of the required infrastructure is extremely small. For this reason, the operators of the Bitcoin DLT have been self-organising in groups, sharing among them the compute power and in turn splitting the rewards received proportionally to their contribution. The term used to describe these groups is "mining pools". The aspect of the mining pools that is primarily of interest to the security of the blockchain is the percentage of the compute power of the DLT system they control. In the Bitcoin DLT it is estimated that almost 50% of the total DLT compute power is controlled by the 4 biggest mining pools [55]. This concentration of power is negatively affecting the decentralization of the DLT as it can allow the manipulation of the data stored on the DLT bypassing the security mechanisms of the consensus algorithm [56]. In fact it can be argued that a large enough mining pool which has significant "stake" in the DLT system shifts the PoW consensus paradigm towards the direction of PoS. Therefore, the security that the PoW consensus algorithm offers as an exchange for the enormous energy consumption it requires cannot by itself guarantee a completely trust-less system as economic incentives can shift the consensus paradigm to a less decentralized direction.

3.5. Conclusions

The key finding of the Technical Specification Guidelines on Energy Efficient Blockchain Systems [27] is that although the available DLT architectures and implementations vary greatly and require deep technical knowledge to understand their operation and mechanics, the relationship between DLT and energy consumption can be understood quite easily when approaching it from the trust dimension. To re-iterate:

> *the energy consumption of a DLT is negatively correlated with the level of trust we place on the operator of the DLT; as trust decreases, energy consumption increases.* [27]

One of the key questions that needs to be answered, before considering DLT as a candidate technology and subsequently selecting among the available implementations, is what is the level of trust one is prepared to accept. As discussed in Section 3.4, this decision will determine which of the available consensus paradigms could be used. This decision has by far the greatest impact on the energy consumption and the sustainability of the DLT.

A second finding is related to the relationship of DLT with the energy efficiency of the equipment used to operate it, which is counter-intuitive. For the PoW DLTs that have enormous energy requirements, the efficiency of the equipment has practically no impact on their long-term total energy consumption. In fact, the total consumption is dependent primarily on the perceived value of assets stored on the DLT. An increase in the efficiency of the equipment will have only a short-term positive effect on the energy consumption. As this improvement becomes noticeable and is exploited by the DLT operators, the PoW consensus algorithm will automatically adjust its difficulty in order to force the network to consume energy of sufficient value to reflect the perceived value of the assets stored on the DLT.

4. Future Directions

DLT can provide ingenious and elegant solutions that were not possible with the technologies available up to now. However, these solutions may have significant undesired side-effects that can negate the value of the whole endeavor. Although a deep technical understanding of the DLT technologies is not always possible, it is important to have a solid understanding of the domain and a set of tools to guide us in an informed decision of if a DLT solution is applicable, possible, desired and of course sustainable.

In this article a review of the standardization activities of ITU that focused exclusively on DLT from 2017 through 2021 was presented and the findings of the ITU-T Technical Specification Guidelines on Energy Efficient Blockchain Systems [27] were analysed in detail, including the mechanisms that lead to the enormous energy consumption of the PoW DLTs. Since then, the ITU focus groups have shifted to other domains like for example the ITU Focus Group on Metaverse (FG-MV) [57] where DLT plays an important role, and new Technical Reports, Specifications and Recommendations have been published focusing on specific aspects of DLT. Given the rapid evolution of DLT and the new algorithms and innovations that take place in this domain, it should be expected that the standardisation activities in this domain will continue for the foreseeable future.

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Abbreviations

The following abbreviations are used in this manuscript:

DLT	Distributed Ledger Technologies
DPM	Data Processing and Management
DeFi	Decentralized Finance
FG	Focus Group
HLA	High Level Architecture
ICT	Information and Communication Technology

ISO	International Organization for Standardization
ITU	International Telecommunication Union
ITU-D	ITU Development Sector
ITU-R	ITU Radiocommunication Sector
ITU-T	ITU Telecommunication Standardization Sector
IoT	Internet of Things
OECD	Organisation for Economic Co-operation and Development
PoA	Proof of Authority
PoS	Proof of Stake
PoW	Proof of Work
SC&C	Smart Cities and Communities
SG	Study Group
WG	Working Group

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