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Evaluating the Barriers to Blockchain Adoption in the Energy Sector: A Multicriteria Approach Using the Analytical Hierarchy Process for Group Decision Making

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Abstract: The blockchain has been proposed for use in various applications in the energy field. Although the blockchain has technical strengths, several obstacles affect the application of the technology in energy services. The scope of this study is to highlight and prioritise the most important barriers to such applications. The first step in this direction is specifying the potential areas of the implementation of blockchain technology in the energy sector. Two useful tools for market analysis were used: Political, Economic, Social, Technological, Legal and Environmental, PESTLE Analysis, and Strengths, Weaknesses, Opportunities and Threats, SWOT Analysis, which examine external and internal factors, respectively. Thus, a list of the most important elements hindering the incorporation of the blockchain in the energy sector was extracted. The detected barriers were classified and ranked by energy and IT experts using the multicriteria method, "Analytical Hierarchy Process for Group Decision Making". The results reveal that legal barriers relating to the complexities of deficiencies of regulations are the most significant, while technological barriers, especially those related to security issues, are also important. Sociopolitical barriers related mainly to lack of trust in blockchain, as well as economic concerns such as high upfront costs, are less influential but should still be considered. The conclusions of the conducted research have the potential to guide market actors in their endeavours to modernise energy systems through the use of the blockchain, assisting them in designing the most appropriate market strategies.

Keywords: distributed ledger technology; multicriteria decision analysis; market analysis; PESTLE; SWOT; digitalisation; energy services

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Citation: Andreoulaki, I.; Papapostolou, A.; Marinakis, V. Evaluating the Barriers to Blockchain Adoption in the Energy Sector: A Multicriteria Approach Using the Analytical Hierarchy Process for Group Decision Making. *Energies* **2024**, *17*, 1278. https://doi.org/10.3390/en17061278

Academic Editors: Antonis A. Zorpas and Michail Tsangas

Received: 1 February 2024
Revised: 1 March 2024
Accepted: 5 March 2024
Published: 7 March 2024

1. Introduction

The European Union has recognised reducing energy consumption and the uptake of energy efficiency as crucial objectives to mitigating the negative consequences of climate change [1]. Thus, it is a strategic goal to modernise energy services and to reduce dependency on fossil fuels so as to protect the environment and enhance quality of life while sustaining economic activity [1,2]. Clean energy transition and shifting towards a more efficient and less energy-demanding society requires intense policies and measures [3]. Furthermore, it is important for both EU member states and companies to remain committed to the targets set towards a carbon-free economy despite the challenges posed as a result of the global crisis due to the COVID-19 pandemic [4].

To ensure an optimal transition towards a more sustainable energy field, it is of vital importance to explore the digitilisation of energy services through the incorporation of innovative technologies and tools [3,5,6]. Examples of such technologies include Artificial Intelligence, Machine Learning and blockchain technology [7]. More specifically, the blockchain was initially introduced by Nakamoto in 2008 [8]. Nakamoto presented a peer-to-peer electronic cash system based on decentralised transactions enabled by distributed ledger technology (DLT). The blockchain is considered a disruptive technological breakthrough because of its ability to guarantee reliable transactions without the need for a third party to control the process [9]. Blockchain's reliability and security stem from the use of cryptography and consensus algorithms [10]. Since the blockchain's initial introduction, researchers have recognised that the potential of this technology is not only limited to digitalised monetary transactions through cryptocurrencies; on the contrary, it can be used in a variety of applications. For instance, blockchain can be used to automate processes or workflows thanks to automatically executed computer protocols, also known as smart contracts [11]. Furthermore, blockchain-based platforms can be used as secure databases [12]. Taking this into consideration, extensive research has been conducted on the exploitation of blockchain in several industries and sectors beyond finance-related applications. For instance, blockchain can be used in the healthcare sector [13], the automotive industry [14], as well as in applications relevant to the Internet of Things [15], supply chain [16], asset tracking [17], distributed identities and identity management [18], security and privacy preservation [19], digital ownership [20], reputation systems [21], education [22] and copyright protection [23].

The scope of this study focuses on the applications of blockchain in the energy field. More specifically, the following research gap has been identified: so far, no studies have concentrated on detecting the wide variety of barriers hindering the full spectrum of potential blockchain applications in the energy field. However, the identification and evaluation of the barriers to such applications is of vital importance since assessing and prioritising them is necessary to assist in the strategic planning of stakeholders involved in the adoption of blockchain in energy. To this end, an approach based on the combination of market analysis tools with Multicriteria Decision Analysis (MCDA) is being proposed. In order to cover the needs and opinions of the different stakeholder categories that are involved in the particular decision-making process, the proposed MCDA method has been applied to a group of decision makers from both the Information and Communication Technology (ICT) and energy sectors.

The paper is structured as follows:

- In Section 1, a general introduction about the current state of the energy sector, as well as a brief description of blockchain technology, are provided. The scope of the paper is also described.
- In Section 2, the methods used for the identification and evaluation of the use of the blockchain in the energy sector, consisting of a literature review, market analysis and the Analytical Hierarchy Process (AHP) for Group Decision Making (GDM), are presented, while the sources of material are also mentioned. The research design and methodological steps are also outlined.
- The results of the implementation of the methodological steps are displayed in Section 3.
- In Section 4, the results are analysed, discussed, and compared with relevant research studies.
- The conclusions are drawn in Section 5.

2. Materials and Methods

2.1. Sources of Materials and Description of the Methods Used

In this section, the methods used within the paper are described, and sources of material and data are also mentioned. The following methods were used:

Literature review: Appropriate keywords related to blockchain (distributed ledger, decentralised, Ethereum, smart contracts, cryptocurrency) and energy (energy management/governance/supervision/control/storage, demand-side management, smart grid/community/metering, microgrid, energy/electricity/power/emission/carbon trading, energy transaction, energy market, carbon footprint, electric vehicle charging, Internet of Vehicles (IoVs), and Vehicle-to-Grid (V2G)) were selected. Based on those keywords, a sample of 200 scientific articles was studied. The publications were found in various databases, including ScienceDirect [24], ResearchGate [25], Scopus [26], and IEEE Xplore [27].

PESTLE Analysis: PESTLE, a market analysis tool, is a variation of PEST analysis. PEST stands for Political, Economic, Social and Technological, while PESTLE also extends to Legal and Economic factors [28]. PEST was originally used to examine the aspects that might affect a product or a service; however, its application is not limited to the business sector. On the contrary, PEST and its variations are also used in research and in engineering applications and projects as a useful tool for determining and recognising potential prospects, barriers, and risks [29]. PESTLE considers the broad external environmental context that affects a product or service and the changes that occur in this context, and then SWOT analysis can be used to interpret these findings to determine the strengths and weaknesses and opportunities and threats of the internal environment.

SWOT analysis: SWOT is a tool that has emerged from the need to recognise the causes that have led to the failure of chosen strategies or plans of businesses [30]. Through SWOT, businesses can detect the factors directly influencing or determining their future, either related to the internal or external environment [31]. These factors include strengths (positive internal factors—related to the present/current situation), weaknesses (negative internal factors—related to the present/current situation), opportunities (positive external factors—related to the potential future/imminent situation), and threats (negative external factors—related to the potential future/imminent situation) [29]. The main advantage of SWOT is its simplicity, which has led to its widespread use, not only in the business world but also in academia [32].

As a methodology, SWOT analysis enables understanding and planning on how to use strengths to benefit from opportunities, identify and repair or sidestep weaknesses, and defend against or avoid any threats [33]. Despite its wide application, the main drawback of SWOT is the fact that the importance of each element cannot be measured or calculated quantitatively, impeding the objective assessment and ranking of the detected factors. However, when combined with MCDM methods, SWOT analysis can provide a quantitative measure and estimation of the importance of each factor [34]. MCDM is a sub-branch of decision-support systems, offering a multitude of methods that can address decision-making problems considering multiple criteria [35]. Several SWOT and MCDM combinations have been applied by researchers in the field of energy. For instance, Papapostolou et al. (2020) used AHP and SWOT in combination with fuzzy TOPSIS to develop a methodological framework towards adopting the most appropriate strategic plan for successful collaborations between countries in the field of renewable energy [36]. Almutairi et al. (2022) combined SWOT, MCDM, and game theory to recognise the best renewable energy development plans for Iran [34]. Akçaba and Eminer (2022) proposed an integrated approach of SWOT analysis, ANP, and fuzzy TOPSIS to rank alternative energy strategies for Northern Cyprus [37]. A similar study was conducted by Ervural et al. for energy planning in Turkey [38].

AHP GDM: As previously mentioned, in this paper, market analysis is combined with the Analytical Hierarchy Process (AHP), an MCDM. A crucial advantage of MCDM methods is their capacity to integrate both quantitative and qualitative approaches, which is ideal for decision-making problems that demand rational solutions under uncertain environments, especially if subjective factors are also involved [39]. The energy sector is, undoubtedly, an environment of increased uncertainty since, besides technical and economic criteria, there are environmental and social elements whose role is vital, and the legal framework is also important. These factors are subjected to constant changes, making their systematic evaluation even more imperative [39].

Although there is a number of MCDM methods used for prioritisation purposes [40], in this particular problem, the AHP method was selected. The literature suggests that AHP is the most preferred MDCA method and one of the most widely used in practice, and its popularity is owed to the fact that it allows comparisons of similar results on an equal footing [41]. It is often used with the aim of comparing competitive priorities [42]. AHP is based on three principles: first, the structure of the model; second, a comparative judgment of the alternatives and the criteria; and third, the synthesis of the priorities.

Owing to its mathematical simplicity and flexibility, AHP is a favourite research tool in terms of energy efficiency, energy management, and renewable energy sources [35]. In the field of blockchain technology, AHP has also been utilised as a decision-making tool. A combined AHP method with a decision-making trial and evaluation laboratory (DEMATEL) method was applied to assess blockchain technology implementation in a circular supply chain management context [43]. A simulation-based AHP approach was used to analyse the scalability of EHR systems using blockchain technology in healthcare institutions by Garrido et al. (2021) [44], while Li and Gong (2022) supported the design of a power grid data management system based on blockchain technology and developed a system security evaluation model with the use of AHP [45]. Murat Ar et al. (2020) utilised the AHP method to evaluate the feasibility of the use of the blockchain in logistics operations [46].

From the above, it is obvious that the AHP method is popular both in the field of energy and blockchain; however, to the best of our knowledge, there are no references in the literature that combine the application of market analysis methods with MCDM, particularly AHP, in order to identify and assess the barriers that hinder the adoption of DLT in energy services. The input needed for the application of AHP was obtained via a questionnaire (see Appendix A) distributed to five decision makers both from the energy and IT sectors who are involved in the adoption of blockchain technology in energy services.

2.2. Research Design and Structure

The methodological steps that resulted in the prioritisation of the barriers to the adoption of blockchain technology in energy services are shown in Figure 1. Having defined the problem, a literature review was conducted to identify the different potential implementations of blockchain technology in energy applications. Examples of real-life implementations have also been presented. The aim of this review was to identify different potential areas of energy services where blockchain can be exploited. Subsequently, market analysis was used as a tool to recognise political, economic, social, technological, legal, and environmental aspects of the identified implementations (PESTLE analysis). The aspects of PESTLE analysis were also reclassified as positive and negative findings and divided into either elements referring to the current situation of blockchain implementations in energy or elements referring to future trends. As a result, strengths, weaknesses, opportunities, and threats were identified (SWOT analysis). The aim of the market analysis was to recognise the full scope of factors—both internal and external—that influence the adoption of blockchain technology in the energy field. Based on the market analysis (on the weaknesses and threats of SWOT analysis in particular), the main barriers to blockchain integration in the energy sector were extracted. They were also divided into four categories. To evaluate the barriers, AHP for GDM was utilised. The aim of the application of the AHP method was to extract a ranked list of the categories of barriers, as well as the prioritisation of the barriers within each category.

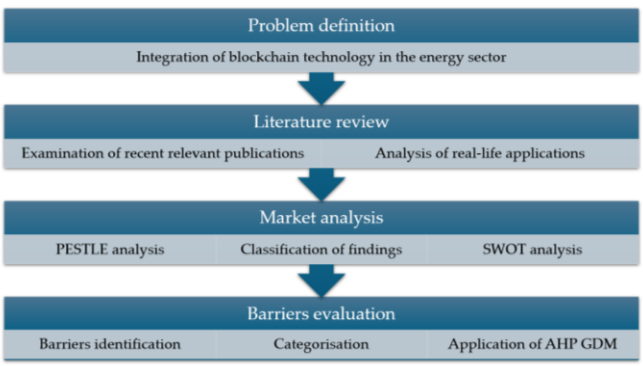


Figure 1. Methodological approach.

3. Results

In this section, the results of each stage of the methodology described above (literature review, market analysis, and AHP for GDM) are presented.

3.1. Review of Blockchain Applications in the Energy Sector

Previous studies, such as [47–49], have highlighted the variety of potential applications of blockchain technology in the energy sector. This review focused on the most recent publications (after 2017) and was based on databases such as ScienceDirect [24], ResearchGate [25], Scopus [26], and IEEE Xplore [27]. The examined articles have been classified into eight categories, as shown in Figure 2.

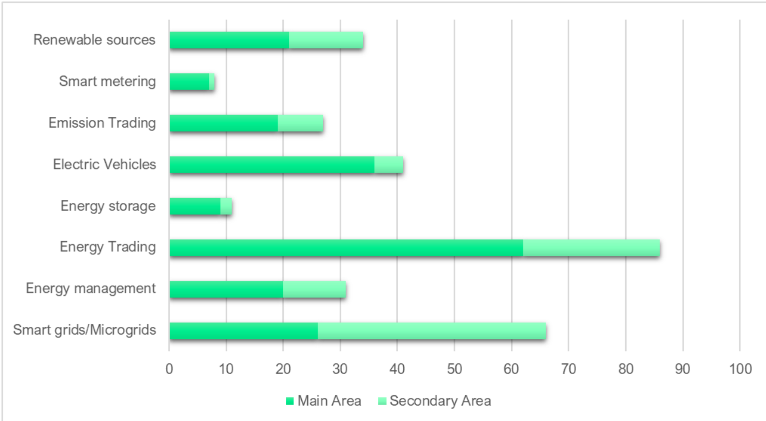


Figure 2. Main and secondary areas of the examined publications.

Many of the proposed blockchain-based solutions for smart grids and microgrids aim to ensure user privacy and security, enabling safe communication and data sharing within the grid [50]. Blockchain models have also been proposed for energy exchange in smart communities [51]. The optimisation and management of grid resources and functions could also be assisted by blockchain technology [52].

Regarding energy management, blockchain technology could support management in a variety of energy systems, such as smart cities [53], microgrids [54], distributed energy systems [55], distribution networks [56], energy hubs [57], and virtual power plants [58]. Furthermore, blockchain models for energy management of smart buildings [59] and smart building communities [60] have been proposed. Blockchain is also a useful tool when it comes to demand-side management [61].

Energy trading is the most common application of blockchain technology in the energy sector. According to the examined publications, thanks to the efficiency of distributed ledger technologies when it comes to transactions and the decentralised nature of the blockchain, various blockchain-enabled platforms for P2P trading in energy markets or among prosumers have been proposed. Such platforms can be implemented in distribution networks [62], smart communities [63] and microgrids [64]. Blockchain can also be combined with forecasting applications in energy markets [65].

The efficient management of energy storage units could guarantee the flexibility of modern energy systems, satisfying demand or acting as a backup source to prevent blackouts. Blockchain models could support energy storage applications by coordinating battery charging and protecting sensitive or personal user data [66,67].

Moreover, the field of electric mobility is very promising in terms of implementing energy blockchains. To be more specific, blockchain models have been proposed for EV charging [68] to support battery management, coordination, and scheduling [69], payments [70], and other applications. Other research has proposed energy trading frameworks for electric vehicles [71]. Blockchain has also been considered a potential tool for Vehicle-to-

Grid (V2G) implementations [72], vehicular grids, or Internet of Vehicles (IoVs) [73], and applications relating to autonomous or smart vehicles [74].

Many research articles have considered blockchain-enabled emission trading. Distributed ledger technologies can be utilised in carbon trading applications for process optimisation [75], carbon emission monitoring [76], and fraud prevention [77]. Few of the reviewed papers consider a combination of emission trading with electricity trading [78]. Renewable certificates [79] or renewable energy credits [80] could also be managed within blockchain frameworks.

Furthermore, several frameworks combining blockchain and smart meters have been proposed. In these frameworks, the security of metering data is considered crucial. Therefore, the privacy protection and safety of user data sharing are prioritised [81].

Regarding renewable sources, blockchain solutions have been proposed mainly for wind [82] and solar applications, specifically for photovoltaic generation [83] and solar energy exchange [84].

Besides the theoretical approaches presented by various researchers regarding the application of blockchain technology in the energy sector, as presented above, relevant endeavours that have been implemented in real life, mainly through pilot projects, have also been examined (Table 1). These endeavours also include several projects funded by the European Union involving various organisations, such as universities, research institutes, and key market players, that is to say, companies active in the energy or ICT field. Some of the projects have been documented by the EU Blockchain Observatory and Forum [85].

Table 1. Real-life implementations of blockchains in energy services.

Project	Description	Source
INTERFACE	A blockchain flexibility trading platform where TSOs, DSOs, FSPs and prosumers can safely transact without any central governing authority.	[86]
BD4NRG	Innovative data governance layer compliant with the International Data Space Association and P2P digital marketplace for heterogeneous tokenised asset compensation.	[87]
BRIGHT	Blockchain technologies supporting new community-enabled ways for engaging consumers in demand response.	[88]
DEDALUS	Blockchain-based solutions to preserve privacy, ensure trusted data governance and sovereignty, enable energy flexibility and data sharing with the aim of deploying effective algorithms and services for residential demand response.	[89]
PLATONE	Blockchain-based P2P trading, data management, data sharing, data certification, grid control, and economic transaction.	[90]
FleXunity	Energy community approach encouraging active involvement of community participants through flexibility and energy sharing supported by secure transaction mechanisms via blockchains.	[91]
PARITY	Local electricity market facilitating automated P2P energy/flexibility trading among prosumers and implicitly integrates a local flexibility market for facilitating the selling of flexibility to smart grid actors.	[92]
WePower	Platform directly connecting energy producers with end clients, allowing energy trading with pricing below the market's threshold.	[93]
Sun Exchange	Crowdfunding platform for investments in small or medium-sized solar energy projects in developing countries.	[94]
InEExS	Smart energy services–business models facilitating the deployment of sustainable technologies (renewables, electric vehicles, heat pumps, Internet of Things, controls, and energy efficiency measures) via blockchains.	[95]

3.2. Market Analysis of Blockchain in Energy

Having examined various blockchain applications in the energy field from both a theoretical and a practical point of view, it becomes clear that the potential implementations are numerous, but the actual efforts to integrate blockchain technology in energy services are still quite premature and rely mainly on pilot projects. Therefore, in order to successfully incorporate blockchains in the energy sector in an effective, efficient, and beneficial way, it is necessary to identify and analyse the prospects and challenges included in this integration in order to recognise the specific obstacles and address them. To achieve this, a market analysis of blockchain adoption in the energy sector was undertaken. PESTLE and SWOT analyses of blockchain in energy have been previously outlined by Papapostolou et al. [96]; however, the market analysis presented in this paper is more extensive and detailed, revealing the full scope of DLT applications in energy services, aiming to provide a comprehensive overview of the internal and external environment.

3.2.1. PESTLE Analysis

Through our PESTLE analysis, we aim to identify various factors that might influence the integration of blockchain platforms and models in energy systems.

Political factor: Our first findings consider the political factors relating to blockchain adoption in the energy sector. Firstly, due to the need for climate change mitigation, decarbonisation targets have become an indefeasible part of policies and political agendas in general [97]. Those targets include reducing carbon emissions and shifting towards cleaner sources of energy [98]. Blockchain-based applications have the capacity to assist in the management of complex energy systems, even when there are a lot of distributed sources of renewable energy [99]. Carbon trading mechanisms [77] and the charging of electric vehicles [69] can also be efficiently supported by blockchains.

Subsequently, energy blockchains have attracted the attention of European institutions. To be more specific, the EU Commission hopes to efficiently integrate renewable energy sources into energy systems and prosumers into electricity markets. As a result, a plethora of challenges have appeared [98,100]. However, blockchains could provide sufficient solutions and help address many of the problems. For instance, their implementation could facilitate the integration of prosumers or small-scale producers in the market. It could also support the effective management of complex energy systems with distributed energy production units [7]. Thus, the EU Commission has already examined the possible implementation of blockchain technology in the energy field [98,100].

However, it should be highlighted that there might be a deficiency of knowledge concerning blockchain because the technology is relatively new. Due to this deficiency, it is possible that political institutions are not fully informed about the prospects of blockchain use cases and the gains of blockchain usage. Furthermore, there might be ignorance regarding the practical aspects and feasibility of specific blockchain applications [101].

Another finding stems from the above-mentioned ignorance. To be more specific, an insufficient understanding of distributed ledger technologies and blockchain leads to uncertainty and hesitance, making its adoption more difficult because it is perceived as risky. Since risk is usually avoided by politicians, uncertainty must be considered a significant obstruction to widespread blockchain implementation [102,103].

Economic factor: The economic factor can be summarised in seven findings. Firstly, we considered the success of cryptocurrencies in the financial sector. Cryptocurrencies have revolutionised transactions, threatening to completely transform the functions of the financial system [101,104]. Digital currencies were the first implementation of blockchain technology and remain the most dominant application of distributed ledger technologies today. Therefore, there is sufficient proof of the efficiency and success of blockchains when it comes to monetary transactions, and thus, its expansion towards other forms of transactions is very promising [97].

Additionally, smart contracts executed via blockchain also promise to revolutionise payments. More specifically, an immediate link with the payment provider can be achieved as intermediaries become obsolete. Furthermore, there have been efforts to incorporate and use data from the real world in these types of contracts [100,104].

It is also evident that the integration of new technologies in various sectors, such as the energy sector, can result in financial benefits because new connections between different stakeholders occur. When it comes to energy blockchains, start-ups, energy utilities, and financial entities need to cooperate, creating innovative strategies and new business models that will reveal more opportunities and profits [97].

In addition, energy blockchains could create opportunities for investments [97]. Nonetheless, scepticism has been observed when it comes to investments in blockchains. Even though the technology has already attracted the attention of numerous start-ups, many companies in the energy sector would still be too hesitant to invest in this technology due to the risks involved in changing their established business models, combined with the lack of adequate technological knowledge. Furthermore, these investments might not be feasible for several businesses due to the intense computational requirements. Medium and small energy enterprises might not be able to financially support the hardware update of their existing resources, which would be necessary for blockchain integration [97,101]. Moreover, companies may incur several expenses since consulting services will be required to help them comply with regulations [97].

It is also important to note that the impact of blockchain on cost be considered. The initial costs of setup, establishment, and maintenance costs are considered to be quite high, which is a reasonable downside stemming from the infancy of blockchain technology [101,105]. Return on blockchain investment is another major concern since, due to the high initial cost, potential blockchain investors worry that the profit margin brought by their investment may be too low [106]. When it comes to whether blockchain will lower or increase transaction costs, researchers have not yet reached a consensus. Some argue that the reduction in transaction fees, the curtailment of failed transactions, and the removal of control by third parties will result in an overall decrease in transaction costs [107,108]. On the other hand, the energy used during transactions may rise, thus increasing the cost. Blockchain technology has also been proposed as a solution to reduce the cost of EV charging applications. In conclusion, how blockchain will influence cost depends on the specific use case and the characteristics of the system; however, careful design and efficient communication between stakeholders increase the chances of long-term cost reductions [105].

Following this, electricity and metering markets are considered. Electricity markets tend to become more and more liberalised. The integration of prosumers in existing electricity markets can be assisted by blockchain, boosting independence from suppliers, operators, and other third parties or intermediating entities thanks to the decentralised nature of the technology [89,96]. Without a centralised authority, trading cannot be easily manipulated, as manipulation would be quickly identified thanks to the transparency offered by the blockchain [91]. The threshold of entrance into the market can be lowered as well. Moreover, many blockchain applications demand the utilisation of metering data generated by smart meters. However, currently, the metering data are only available to specific entities and can be managed exclusively by them, which is a hurdle for blockchain adoption. The fact that the power metering market is not yet liberalised must be considered as a significant barrier for blockchain applications in smart grids [97].

Finally, blockchain-based crowdfunding platforms could finance sustainability projects around the world so as to boost social action aiming to enhance energy access or reach energy transition goals [94].

Social factor: Regarding the social aspect, six findings are considered. The first finding concerns the approval of decentralised P2P energy trading schemes by society. According to research conducted by Borges et al. (2022), there is a social shift towards P2P and the digital trading of electricity (66% of potential prosumers viewed P2P energy trading as a positive update). However, many participants remained sceptical. Decentralisation of the energy trading system and the incorporation of new technologies in energy services were perceived as too risky or unsafe by a non-negligible number of potential prosumers [106].

The functionality of smart communities lies largely in data sharing, but lots of prosumers will likely feel uncomfortable and refuse to share energy data. Furthermore, there is a possibility that the algorithm will favour specific participants of the grid in the early stages of its development. Other issues and concerns revolve around the security and reliability of the system, policy uncertainties, and the possibility of errors that might not be easily reversible once they have occurred [103,104]. For example, it is likely that a mistake in a smart contract cannot be resolved after its execution. Lastly, some potential prosumers do not trust a completely digitalised system that lacks an alternative form of manual control. There are doubts regarding the behaviour of the system during unpredictable situations or special occasions, such as holidays. Emergency and backup plans could alleviate the social reluctance surrounding P2P trading schemes [106].

Secondly, bitcoin and blockchain are often perceived as two undistinguished technological innovations, which leads to misconceptions [101]. Bitcoin has been associated with illegal activities (e.g., money laundering, hacking, and fraud) [109]. As a result, distributed ledger technologies are viewed as untrustworthy, and their potential applications in non-financial fields are neglected [101]. The misconceptions are also encouraged by a general lack of understanding of blockchain, which reinforces the lack of trust [101].

Another finding stems from the previous two findings. Misconceptions and a lack of solid understanding create uncertainty. Therefore, blockchain adoption is considered risky, and generally, society tends to avoid risk [101,102]. Risk aversion and avoidance might be connected to the fact that novel technologies that have not been widely tested are immediately and instinctively regarded as untrustworthy. Blockchain would likely be a more socially acceptable solution if further practical tests revealed that it is, in fact, a reliable and secure technology [101,103].

Lastly, the potential positive social impact of blockchain applications in the energy transition of developing countries must not be neglected. As mentioned in the economic section of our PESTLE analysis, blockchain can support alternate financing models, such as crowdfunding. Such models can boost social action, enable initiatives and be very beneficial. Not only could they assist the energy transition in the developing world, but also enhance energy access around the globe [97].

Technological factor: The technological factor of blockchain implementations in the energy field could be regarded as the most substantial section of our PESTLE analysis. Firstly, the digitalisation trend is prominent in a wide variety of sectors, and the energy sector is no exception. Disruptive technologies, including blockchain, promise to improve the efficiency of energy systems. Thanks to digitalisation, the participation and integration of many users in electricity markets could be accelerated [101,103].

Moreover, blockchain technology could be ideal for P2P energy trading applications thanks to its decentralised nature [98]. Problems caused by third-party failure can be eliminated [105]. Transparency is also a key feature of blockchain technology, which would be very useful in energy applications. Since transactions and activities would be broadcasted and monitored by all the nodes of the network, manipulation in the energy market or fraud in emission trading would be prevented [100,105]. Data stored in a blockchain are generally immutable, which is crucial, for instance, when tracking the origin of consumed electricity [100,103]. The immutability of blockchain largely guarantees data accuracy [104]. The blockchain structure determines that once a block is added to the chain, it can no longer be edited or deleted. Data are always accessible after they are logged into the chain [105]. Blockchain-based systems are generally considered highly secure and reliable since all network participants can create blocks and keep a replica of the data. Consequently, the network cannot be easily damaged [100]. Security is further increased by the decentralised nature of blockchain and cryptographic algorithms. Moreover, identity protection is ensured thanks to the anonymity offered. The data stored in the chain include information about the transactions. No personal information about the network participants is revealed, and therefore, user privacy is not violated [105]. As mentioned, blockchain security stems from cryptography; however, we cannot rule out possible fragilities of the cryptographic algorithms over the course of time [100,110]. The development of quantum computers could endanger cryptographic mechanisms, as a powerful quantum computer might, theoretically, be able to crack blockchain encryption [100,111]. The possibility of data protected by cryptography being decrypted in the future reveals a potential threat posed by decentralisation since a copy of the encrypted data is available to all network nodes. Therefore, a malicious participant could decrypt previously saved data [100,106]. There are also concerns surrounding the security of keys, both private and public, which are represented by strings of alphanumerics and are utilised in transaction procedures. The development of deanonymisation techniques has also been reported [101].

Irreversibility and possible data deletion are also notable barriers to blockchain implementations. The output of the smart contract code cannot change or be averted. Furthermore, a possible faulty transaction cannot be undone. The identity of the participant receiving the mistaken payment will not be easily traceable due to anonymity [101,106,112]. Generally, code modifications to blockchains are challenging, and the requisite effort is substantial since approval of the updated code by the majority of nodes is required [100]. Limited scalability is a major issue commonly identified in blockchain-related literature. The term "scalability" describes the capacity of a system to function properly despite the augmentation of the amount of work required caused by scale expansion [113,114]. Scalability issues impact throughput, latency, and speed. Transaction speed also depends on the selected consensus algorithm. For instance, the PoW algorithm used in Bitcoin can generate about seven transactions per second. The orderly chained data structure of blockchain makes the process of transactions time-consuming since all nodes need to traverse all records in the chain. Speed is also quite limited when blockchains function as a database. To be more specific, this issue has been referred to in the relevant literature as a "slow query" [105,106,113]. The geographical location, as well as the number of network nodes, can also influence speed [100]. Block size can also cause problems. The blocks have a fixed size, which theoretically increases the throughput; however, this is not the case in a large-scale blockchain system. Request submission speed may surpass block generation speed, which could lead to server congestion, unprocessed requests, and, in a worst-case scenario, denial of service. However, oversized blocks could also be problematic [113]. Another issue is the storage procedure in blockchain models. Since the record of transactions is saved by all miners, redundant data remain on the chain. This can cause considerable problems in a large network. Thus, appropriate storage mechanisms and resources that can handle large amounts of data are needed [101,115–117].

Another aspect to be taken into account is the fact that blockchain platforms may be susceptible to cyberattacks (double spending, 51% attack, selfish mining, withholding attack, balance attack, nothing-at-stake attack, bribery attack, long-range attack, eclipse attack, distributed denial of service (DDoS) attack, Sybil attack) [100]. An attack might aim to change the prices of a blockchain-based trading system [106]. A 51% attack is more likely to succeed during the early formation stages of a blockchain network [101].

Blockchain can offer the flexibility that modern energy systems and distribution grids require. The energy produced by renewable sources varies throughout the day. Therefore, energy management becomes more challenging. There is a need for effective demand-side management, monitoring, and synchronisation of different sources, including storage units and emergency backup power supplies. Efficient management can be achieved using blockchains combined with sensors and smart meters [97].

So far, energy blockchain applications have been tested through simulations or small-scale projects. Not enough practical tests have been conducted, and, as a result, the behaviour of the external physical system cannot be predicted [7]. The risk of blockchain implementation in existing infrastructure is considered high since distribution and transmission facilities are very important, and the energy supply should not be jeopardised; therefore, whether it is acceptable to risk the functions of the existing system is debatable. Voltage levels, harmonics, frequency, and power flow might change significantly if a blockchain network is implemented in a real distribution system [97]. Solutions based on blockchain may not be able to offer all the services provided by current facilities, especially during the early stages of their integration into existing infrastructure [101].

The energy data that are processed and stored do not depend on the blockchain model itself. On the contrary, data are generated by the external system. However, the number of existing smart meters might be too low to support blockchain-based platforms. The computational capabilities of smart meters might be inadequate as well [103]. Therefore, careful design of the blockchain platform is not sufficient if the "off-chain" system cannot operate adequately and properly, providing reliable data [103,105].

Lastly, other modern technologies are of vital importance when the implementation of blockchain in energy is considered. Data from the real world can be transferred and integrated into smart contracts using AI. Concerns surrounding data privacy could subside thanks to deep learning because users might be able to obtain better control of their data rights. Advanced data analysis could reinforce blockchain transparency by tracing abnormal activities. Hardware–software communication is facilitated by IoT technologies, and smart meter infrastructure can be enhanced using digital twins [103,113].

Legal factor: As far as the legal aspect is concerned, there are five findings to be considered. Firstly, there is policy uncertainty surrounding blockchain technology. Policies are undoubtedly a deciding factor [97]. Due to the fact that it is a relatively new technological advancement, respective regulations have not yet been developed, which impedes implementation across various sectors [101]. The legal vacancy is a decisive factor since, in several use cases, involvement by an expert in legal issues might be necessary to address a conflict, which might ensue, for example, by a faulty transaction. However, there are no specific guidelines for the legislator to follow [110,118].

It is important to mention that, once formulated, regulation is expected to be complicated or even considerably different depending on the geographical region. Regulatory complexity could discourage political institutions and market actors. Thus, blockchain might not be utilised to its full capacity [97,103].

Moreover, there is a lack of legally enforceable standards. Standardisation is of vital importance, especially when it comes to the management of digital identities or Application Programming Interfaces (APIs). The interoperability between different technologies and physical facilities is prevented due to the lack of recognised standards [100,101,119].

In addition, although regulatory bodies have begun to explore possible legal frameworks for blockchain markets and cryptocurrencies, the assessment of legal aspects of smart contracts has been neglected. Contrary to conventional contracts, smart contracts are written using code and processed by computers. The legal enforceability and regulatory compliance of conventional contracts are ensured by the appropriate legal language and terminology. To be legally valid, contracts must meet specific requirements, such as reciprocal consent, statement and approval of a valid proposal, proper, sufficient, and careful examination, and legality [106].

Lastly, the compliance of actions in blockchain platforms with the General Data Protection Regulation (GDPR) framework of the EU should be examined [100]. Whether the personal information and data of EU residents could be included and available within smart contracts is questionable and has not yet been clarified [100,106].

Environmental factor: We consider four findings regarding the environmental aspect of blockchain implementations in the energy field. Firstly, as mentioned in the political aspect, the digitalisation of energy systems and services through blockchain and other novel technologies could enhance the management of the systems and facilitate the achievement of energy transition goals [97,98].

Furthermore, blockchain technology can be utilised in carbon trading. To be more specific, the technology ensures transparency and could thus prevent problems (e.g., frauds) that often occur in carbon trading applications [77,103].

Thirdly, platforms based on blockchains can be used to track the source of the consumed energy [103]. Encouraging consumers to be aware and have control over their energy mix could have a positive environmental effect [106].

Nevertheless, computational intensity resulting in high energy consumption of blockchain algorithms is a notable barrier. The mining procedure in a blockchain system is achieved through consensus algorithms such as Proof of Work (PoW). These algorithms guarantee the security of the system and the honesty of the users and ensure the validation of the transactions. However, the amount of energy required for PoW is enormous. Alternative consensus algorithms have been proposed to reduce energy consumption and expenditure, such as Proof of Stake (PoS). For example, Ethereum has switched from PoW to PoS and significantly reduced the required computational power [101,103].

The PESTLE analysis is depicted in Figure 3.

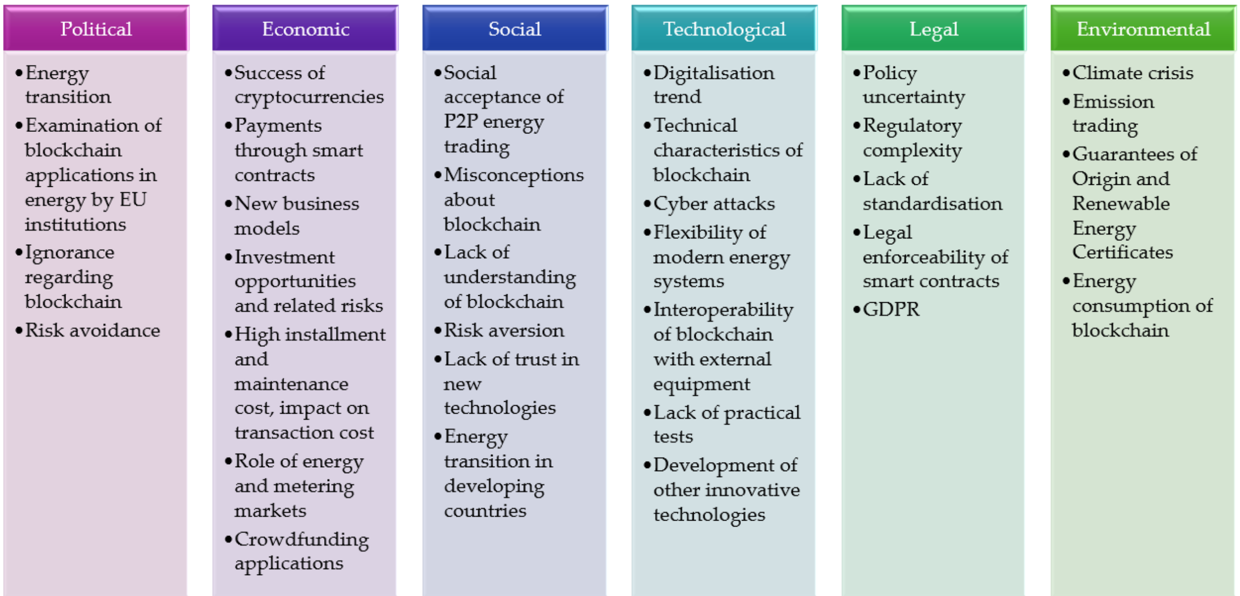


Figure 3. Market analysis (PESTLE) of the external factors that affect blockchain implementation in the energy sector.

3.2.2. SWOT Analysis and Identification of Barriers

The SWOT analysis presented in this section, which is then combined with AHP, relies on the findings of the PESTLE analysis. Regarding the political factor, there are two advantages: the potential support of blockchain technology in energy transition, which has increasingly become a priority for politicians and the fact that European institutions have explored the possible implementations of blockchain technology in the energy sector. The economic factor has seven advantages, which are the success of cryptocurrencies in the financial sector, the possibility of easier payments via smart contracts, emerging new business models, potential reductions in transaction costs, the liberalisation of electricity markets, and the support of sustainability projects via crowdfunding platforms. As for the social factor, there are two advantages, which are the cultural shift towards P2P trading and the positive impact of social initiatives for sustainability enabled by crowdfunding platforms. Regarding the technological factor, there are four advantages: the digitalisation trend in the electricity sector, the technical advantages of blockchain technology, the need for flexibility in modern energy systems, and the development of other disruptive technologies. The four advantages of energy blockchain implementation for the environment are the potential positive impact on modern systems that are more environmentally friendly to comply with the requirements to alleviate the effects of the climate crisis, fraud prevention in emission trading, the management of Guarantees of Origin and Renewable Energy Certificates by blockchain models, and the alternative less-energy-intensive consensus mechanisms.

On the other hand, the two disadvantages of the political factor include the ignorance surrounding blockchain technology and the tendency of politicians to avoid risk. Regarding the economic factor, there are three disadvantages: the doubts about whether a blockchain investment will result in an appreciable return, the possible high costs, and the lack of liberalisation of the metering market. There are five disadvantages concerning the social factor, which are the possible lack of social acceptance of decentralised P2P trading, the misconceptions regarding blockchain, the lack of understanding of the technology, which results in risk avoidance, and the fact that new technologies are considered untrustworthy. The technological factor has four disadvantages: the technical constraints of blockchain technology, cyberattacks, the need for interoperability between blockchains and physical infrastructure, which results in uncertainty regarding the behaviour of the external system, and a lack of large-scale practical tests. As for the legal factor, the five disadvantages are policy uncertainty, regulatory complexity, lack of standardisation, questionable legal enforceability of smart contracts, and uncertainty about the compliance of blockchain applications with GDPR law. Finally, regarding the environmental factor, there is one disadvantage, which is the high energy consumption of PoW.

The SWOT analysis is presented in Figure 4.

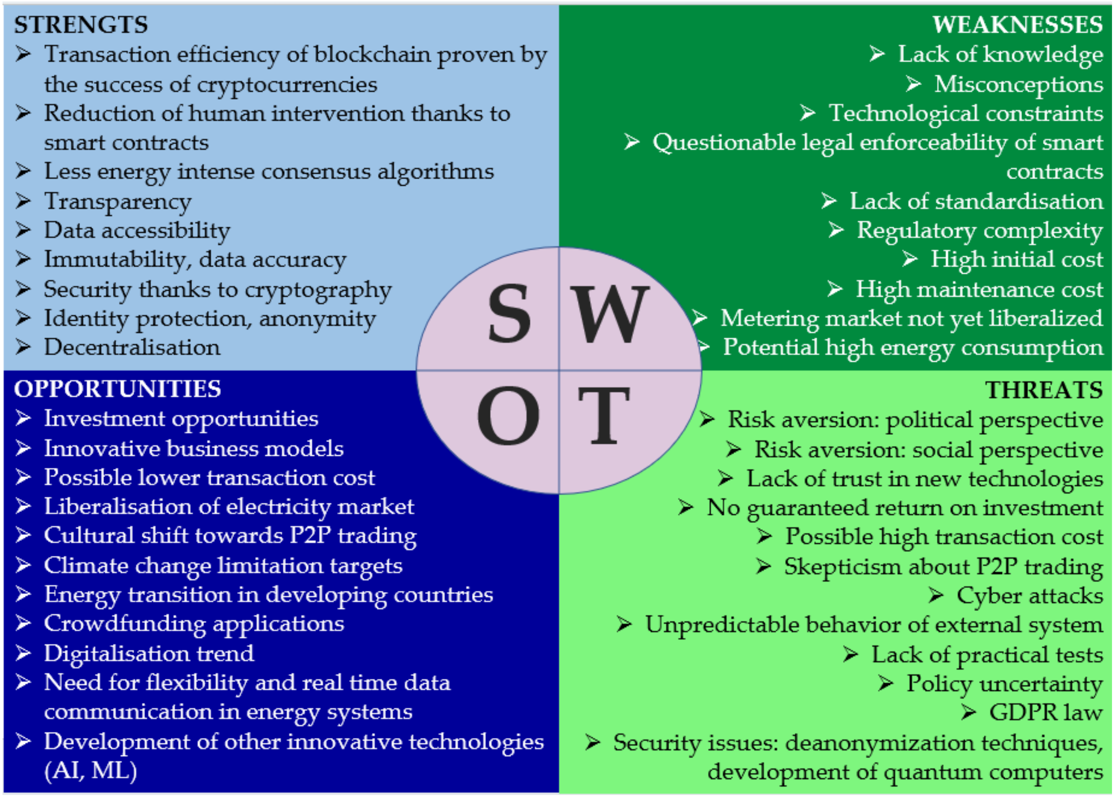


Figure 4. SWOT analysis of blockchain implementation in the energy sector.

The threats and weaknesses of SWOT analysis are the main barriers to blockchain integration in the energy sector, and they can be divided into four basic categories: technological, sociopolitical, legal, and economic, as shown in Figure 5.

The reason why the social and political barriers are merged into one category is the fact that both categories are relevant to the adoption of blockchain technology as perceived by those who are not familiar with the technology or do not have sufficient technical expertise to understand the implications of its incorporation into energy services. The environmental category was also absorbed into the technological category since only one barrier was recognised within the environmental factor of PESTLE: the energy consumption of the consensus algorithm in PoW. Thus, it is also a barrier of a technological nature.

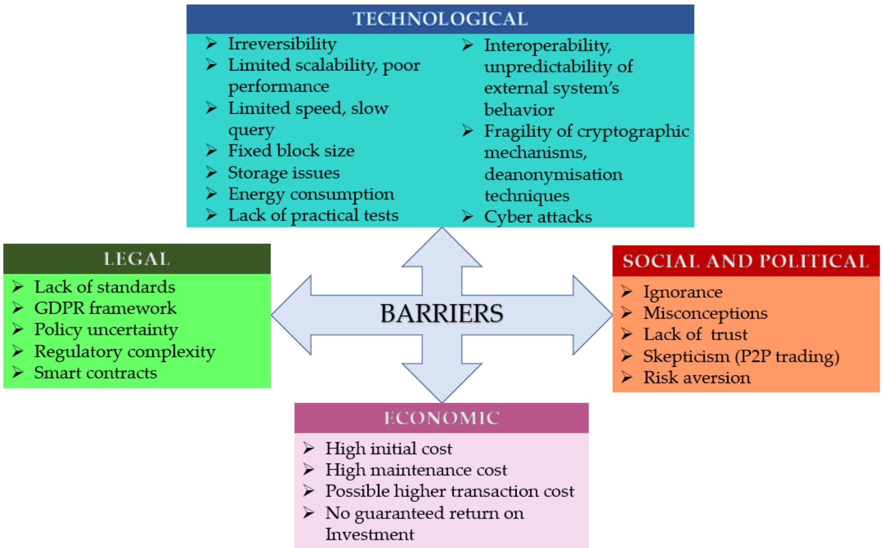


Figure 5. Barriers to blockchain integration in the energy sector.

3.3. Analytical Hierarchy Process

Having recognised the barriers to blockchain adoption in the energy sector, an appropriate MCDA method must be selected to evaluate them. Having examined several previous applications of MCDA in the energy sector [2,5,34,35,40,120–125], the AHP method was selected.

AHP has not been previously used with the aim of evaluating all the impediments, both technical and non-technical, related to the broad spectrum of blockchain applications in the energy sector. Several reasons justify the selection of AHP GDM as the most suitable method for the examined problem. The result of the method is a ranked list of the examined criteria, which is useful since the scope of the decision-making problem is the prioritisation of the identified barriers. This method allows for the aggregation of the opinions of multiple decision makers (DMs), which is important because it is beneficial to combine the perspectives of the energy and ICT sectors. To aggregate the feedback of the five DMs, the row geometric mean prioritisation method and the aggregation of individual judgements were performed. The steps followed are presented in Figure 6.

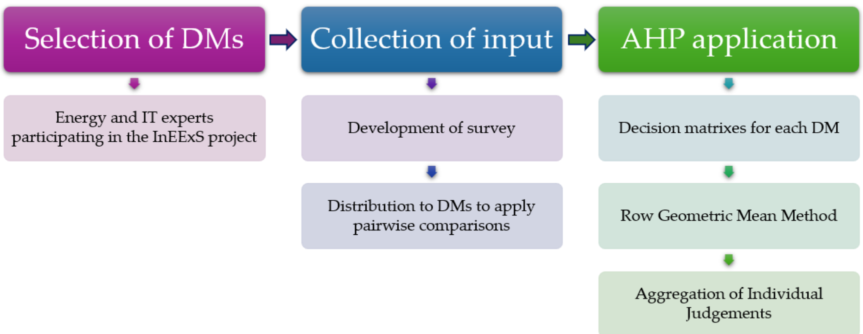


Figure 6. Steps towards AHP application for the evaluation of barriers of blockchain adoption in the energy sector.

Step 1: Selection of Decision Makers (DMs): The decision makers (Table 2) that participated in the process are participants of the EU-funded project InEExS (Innovative Energy (Efficiency) Service Models for Sector Integration via Blockchain) [95]. InEExS aims to deploy integrated smart energy services, emphasising the development of business models that allow for the integration of blockchains in a broad spectrum of energy applications. The developed business models focus on the tokenisation of energy savings, the uptake of energy efficiency, the facilitation of flexibility services, the inclusion of non-energy benefits in the provided services, and cooperation between heterogenous stakeholders and market segments. Therefore, it becomes clear that the selected decision makers represent both the energy and the ICT sectors. They are also familiar with blockchain applications in the energy field because they have examined such applications in the context of the business cases deployed in the InEExS project.

Table 2. Decision makers (DMs).

DMs	Brief Profile Description
1	Research and development (R&D) project manager in energy utility
2	General manager in energy consulting company
3	Research scientist on blockchain technology
4	Head of blockchain research
5	Member of research institute

Step 2: Collection of input: To apply AHP, the DMs need to make 2-way pairwise comparisons between the criteria based on a 9-point scale, as shown in Table 3 [126].

Table 3. The AHP scale.

Scale	Relative Importance
1	Equal importance
3	Moderate importance of one over the other
5	Strong or essential importance
7	Very strong or demonstrated importance
9	Extreme importance
2, 4, 6, 8	Intermediate values

To collect the input from the DMs, a survey was developed (see Appendix A).

Step 3: AHP application: If C = $\{C_j \mid j = 1, 2, \ldots, n\}$ is the set of criteria, the pairwise comparisons between criterion i and criterion j results in a square matrix A, where a_{ij} indicates the relative importance of criterion i with respect to criterion j, as specified by the decision maker. Additionally, $a_{ij} = 1$ when i = j and $a_{ji} = 1/a_{ij}$ [126].

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \alpha_{n1} & a_{n2} & \cdots & \alpha_{nn} \end{bmatrix} \tag{1}$$

Having obtained comparisons from each decision maker and formulated the matrixes, the row geometric mean for each decision maker and each criterion is calculated through the use of Equation (2) [127].

$$w_i = \frac{\sqrt[1/n]{\prod_{j=1}^{n} a_{ij}}}{\sum_{i=1}^{n}\left(\sqrt[1/n]{\prod_{j=1}^{n} a_{ij}}\right)} \tag{2}$$

Subsequently, the consistency of each decision maker is calculated using Equation (3) [128]:

$$GCI(A) = \frac{2}{(n-1)(n-2)} \sum_{i<j} \left[\ln(a_{ij}) - \ln(w_i) + \ln(w_j)\right]^2 \tag{3}$$

The decision makers are considered consistent based on defined benchmarks [129]:

$$\overline{GCI} = 0.31,\ n = 3 \tag{4}$$

$$\overline{GCI} = 0.35,\ n = 4 \quad (5)$$

$$\overline{GCI} = 0.37,\ n > 4 \quad (6)$$

At this stage, the AHP results for each decision maker have been acquired, and thus, their input can now be aggregated. Through the aggregation of individual judgements, the elements of the aggregated judgement matrix are calculated. The aggregated judgement matrix (see Equation (7)) is derived from the elements of the matrixes of each decision maker (see Equation (1)). In Equation (7), λ represents the weights assigned to each decision maker [130].

$$\alpha_{ij}{}^{(c)} = \prod_{k=1}^{m} \left(a_{ij}{}^{(k)} \right)^{\lambda_k} \quad (7)$$

Based on the aggregated matrix, the collective priority vector is extracted.

$$w_i{}^{(c)} = \frac{\sqrt[1/n]{\prod_{j=1}^{n} a_{ij}{}^{(c)}}}{\sum_{i=1}^{n} \left(\sqrt[1/n]{\prod_{j=1}^{n} a_{ij}{}^{(c)}} \right)} \quad (8)$$

Through the application of the methodology described above, the categories of barriers (see bold) and the individual barriers within the categories are ranked. The results are shown in Table 4.

Table 4. Results: ranked list of barriers.

Identifier	Ranking	Criterion	Collective Priority Vector
C3	**1**	**Legal Barriers**	**0.550993**
C3.4	1.1	Regulatory complexity	0.310113
C3.5	1.2	Smart contracts	0.26008
C3.3	1.3	Policy uncertainty	0.181751
C3.2	1.4	GDPR	0.14428
C3.1	1.5	Lack of standardisation	0.103776
C1	**2**	**Technological barriers**	**0.206181**
C1.10	2.1	Cyberattacks	0.1813
C1.5	2.2	Storage issues	0.1683
C1.8	2.3	Interoperability/unpredictability of external's system behaviour	0.1473
C1.9	2.4	Fragility of cryptographic mechanisms/deanonymisation techniques	0.1222
C1.3	2.5	Limited speed/slow query	0.1059
C1.7	2.6	Lack of practical tests	0.078
C1.2	2.7	Limited scalability/poor performance	0.0648
C1.1	2.8	Irreversibility	0.0486
C1.6	2.9	Energy consumption	0.0436
C1.4	2.10	Fixed block size	0.04
C2	**3**	**Sociopolitical barriers**	**0.145392**
C2.5	3.1	Risk avoidance	0.320129
C2.3	3.2	Lack of trust	0.25503
C2.1	3.3	Ignorance	0.233954
C2.4	3.4	Skepticism (P2P trading)	0.115632
C2.2	3.5	Misconceptions	0.075256
C4	**4**	**Economic barriers**	**0.097434**
C4.1	4.1	High initial cost	0.486058
C4.4	4.2	No guaranteed return on investment	0.212696
C4.2	4.3	High maintenance cost	0.151625
C4.3	4.4	Possible higher transaction cost	0.149622

In Figure 7, the priority vectors of each decision maker are visualised, derived from the calculation of row geometric means for each DM (w_i). The collective priority vectors ($w_i{}^{(c)}$) and the weights assigned to the DMs are also demonstrated.

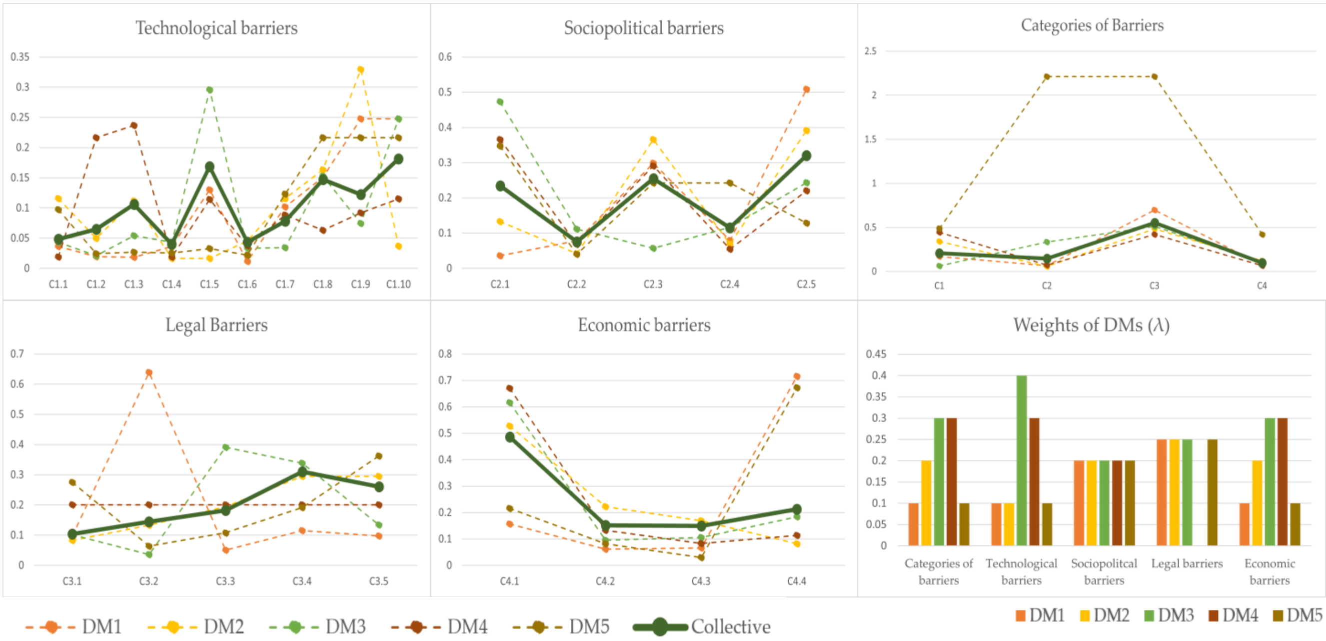


Figure 7. Results of AHP GDM application on barriers of blockchain adoption in energy.

4. Discussion

Despite the fact that blockchains are a relatively new distributed ledger technology, their incorporation in energy services has been examined both in research and in industry, demonstrating a variety of potential applications in energy management, energy and carbon trading, smart energy systems, including distribution networks, microgrids, and energy communities, electricity storage, electric vehicles, smart metering, and renewable energy generation and management, as proven by our literature review. Areas of blockchain applications in the energy sector have also been identified in other relevant reviews, such as [38–40,97]. To ensure effective and beneficial adoption of blockchain in the energy sector, careful analysis and strategic planning are required.

The market analysis highlighted that blockchain attributes, such as transparency, decentralisation, immutability of the data, and privacy preservation through cryptography and anonymity, make blockchain quite attractive for energy applications, especially considering the modern needs of the energy sector that favour the adoption of new technologies. Political institutions, as well as society as a whole, have recognised the urgent need to modernise energy systems. Furthermore, several companies have attempted to test the potential of blockchain technology in the energy sector and have created opportunities for new business models. However, through market analysis, several sociopolitical, economic, legal, and technological barriers were recognised. The results of the overall ranking of the AHP analysis revealed important outcomes compared to other research results in the field of blockchain technology.

Overall ranking: According to the final ranking of the barriers affecting blockchain adoption in energy services, the lack of a legal framework and the various obstacles it entails are considered to be of vital importance, as legal barriers are the first overall category. Technological barriers are the second most important category, followed by sociopolitical and economic barriers.

Legal barriers: According to the decision makers, the complexity of regulations is the most crucial barrier. This is expected, as this issue also influences other categories. As mentioned, a lack of a comprehensive and well-defined legal framework discourages blockchain adoption (thus, it is linked to sociopolitical barriers). In addition, to deal with the complexity of the regulations and legal vacancies, companies need to consult legal experts, thus increasing their overall expenses (thus a linkage with economic barriers is detected). However, it is interesting that DM4 preferred not to compare the legal criteria, possibly because they considered that they lacked the necessary expertise and knowledge to make reliable comparisons. The importance of prioritising legal barriers and forming policies and regulatory frameworks has also been recognised in other studies, such as Diestelmeier (2019) [89], highlighting the urgency to provide incentives and strike a balance between self-responsibility and consumer protection. Furthermore, the legal framework must not be generalized. Instead, it should sufficiently determine the processes and design for specific use cases and applications, which further proves the usefulness of our study since the full spectrum of energy applications in the energy sector is considered. **Technological barriers:** Technological barriers, which are the most numerous, are evaluated as second in the ranking. It is noteworthy that experts in the energy field ranked technological barriers higher than the decision makers of the ICT sector. In this category, higher weights were assigned to decision makers who specialise in blockchain technology. They also achieved the smallest GCI coefficients. Although these coefficients do not prove the accuracy of the answers, low GCI values indicate that the decision maker is consistent and has a fairly clear picture of the relative importance of the criteria. In this category, risks related to blockchain security emerged as the most important. Thus, it becomes clear that stakeholders prioritise security concerns over issues related to blockchain performance or speed, although these issues are also quite important. Of course, it should be considered that the decision makers not only considered the importance of the obstacles themselves but also how easy or difficult these obstacles can be overcome. An interesting result is the fact that the problem of storing unnecessary data on blockchain is second in the final ranking of technological barriers, following cyberattacks, although this topic is not very often mentioned in the relevant literature and is certainly less mentioned than other technological constraints, such as the problem of scalability, which is a very commonly detected barrier, as also highlighted by other studies, such as the review conducted by Erturk et al. (2019) [97]. However, a study conducted by Zhou et al. (2021) evaluating the obstacles of blockchain integration in power trading using the DEMATEL approach placed the storage of redundant data in the top five most influential barriers (the barrier is referred to as "data maintenance") [101].

Technological barriers have been recognised by many researchers and are definitely a highly influencing factor, which is why it may come as a surprise that this category of barriers is not the first in the overall ranking. However, it must be noted that, when evaluating barriers, the decision makers also consider how likely it is to find solutions and overcome those barriers in the near future. The temporary nature of technical constraints related to blockchain technology has also been highlighted by previous researchers, such as Sadhya and Sadhya (2018) [92]. On the contrary, sufficiently defining a regulatory framework is not something that the stakeholders involved directly in the applications of blockchain technology in the energy sector can control. In other words, especially for the type of decision makers involved in the AHP application presented in this study, the legal factor could be considered more significant because it is harder to influence and find appropriate mitigation strategies. Perhaps the results could differ if policymakers were involved in the decision-making process, which is something that will be explored in future research.

Sociopolitical barriers: The prioritisation of sociopolitical barriers seems to have been more difficult for decision makers since the highest GCI coefficients were found in this category (meaning that the decision makers were less consistent). This is not surprising since the barriers in this category are more similar to each other and, thus, more challenging to compare. However, this might be an indication that the decision makers are more uncertain in this domain, and the stakeholders do not have a clear understanding of the sociopolitical dimensions of the adoption of blockchain technology in the energy sector.

Economic barriers: Finally, when it comes to the economic criteria, it appears that the initial cost of installing blockchain-based systems is a leading deterrent to their adoption. On the other hand, the possibility of increasing transaction costs does not seem to affect the integration of blockchain technology into the energy sector as much, according to the decision makers. Perhaps this is an indication that transaction costs are actually more likely to be reduced, particularly thanks to the development of non-energy-intensive consensus algorithms.

The results of the study, particularly concerning PESTLE analysis, highlight the interconnection and interdependence between different factors of blockchain applications in the energy sector, which also aligns with previous studies on the subject. For instance, Ahl et al. (2022) identified the opportunities and challenges emerging from the interrelations between technological, economic, social, environmental, and institutional factors through a stakeholder consultation approach consisting of semi-structured interviews with professionals [94]. However, [94] focused on the national context of Germany, while our study aims to present the implications of blockchain adoption in the energy sector in the broader context of the EU. The prioritisation of barriers also aligned with previous research. More specifically, Zhou et al. (2021), using DEMATEL to evaluate obstacles to blockchain applications in power trading, found that a lack of practical tests, a lack of standardisation, particularly in smart contracts, security issues, data maintenance, and regulatory uncertainty, were the key obstacle factors [101].

The results of the study may have significant implications for various stakeholders involved both directly and indirectly in the integration of new technologies, such as blockchain technology in the energy sector, as well as energy transition in general. More specifically, based on the results of the market analysis and the prioritisation of barriers, especially within the legal and sociopolitical categories, policymakers can identify the vacancies and problems that deter blockchain technology from becoming a widely used technology in the energy sector. Thus, they are able to define the necessary adjustments that need to be made to policies and regulations to encourage the exploitation of distributed ledger technologies in energy services. Furthermore, energy service providers from various sub-sectors of the energy field, ranging from grid operators to energy retailers and utilities, can use this study as a reference point so as to understand the benefits and opportunities arising from the applications of blockchain technology without neglecting the challenges. Furthermore, taking the ranking of barriers into account, they can make more informed decisions about the design and development of mitigation strategies for identified risks by prioritising the aspects that are more influential. Blockchain developers and other IT experts may also benefit from the study, focusing on the ranking of the technological barriers so as to put more effort into finding solutions for the most pressing challenges in this domain while also gaining an overview of the non-technical issues that may occur within their endeavours to implement energy services supported by blockchain. The heterogeneity of stakeholders involved proves the necessity to use group decision-making techniques.

The proposed methodology, consisting of a literature review, market analysis, the identification of barriers, categorisation of barriers, and ranking of categories and individual barriers within them using AHP GDM, could also be used as a stand-alone element in different decision-making problems in different fields since it provides concrete steps that start from extensive analysis of internal and external factors and leads to the detection and prioritisation of barriers in cases where more than one type of stakeholder are involved.

5. Conclusions

In this paper, a combined approach consisting of market analysis using the SWOT and PESTLE tools and the Analytical Hierarchy Process for Group Decision Making has been applied and presented. The market analysis highlights that the research hypothesis of the paper is valid, meaning that there are numerous barriers hindering the adoption of blockchain technology across sectors but no efforts to systematically evaluate, prioritise, and overcome said barriers.

According to the prioritisation of the identified barriers through the use of AHP GDM, the most significant obstacles are those related to the legal side of blockchain applications in energy systems, and the most substantial barrier is the expected complexity of regulations and whether a specific institutional framework for distributed ledger technology in energy systems should be established. The legal barriers are followed by technological barriers.

Security-related threats, i.e., cyberattacks, are prioritised in this category. Aversion towards risk was the most dominant barrier of the third category, that is to say, sociopolitical barriers. Finally, from an economic point of view, the high initial cost of installing blockchain, which can be discouraging for prospective investors, was identified as the major hurdle.

Overall, the use of AHP was proven to be the ideal solution to handle the examined decision-making problem thanks to the advantages and properties of the method. The methodological approach presented in this paper can be used as a reference point for various market actors and stakeholders involved in the adoption of blockchain technology in the energy sector since a very wide spectrum of the key applications of blockchain technology in the energy sector, the factors that affect those applications, as well as the difficulties and positive elements that accompany them, are presented, examined, and analysed. Furthermore, the identification and prioritisation of barriers is a first and necessary step in developing strategies, while it is clear that both energy and technological perspectives must be taken into account when considering the implementation of blockchain technology in the energy field.

The results of the research might also be applied in the context of the EU-funded project InEExS. Through the business cases of the projects, the results can be further analysed, practical solutions and strategies to address the identified barriers can be examined and implemented, and key stakeholders can be engaged in the process, ensuring that the lessons learnt and key takeaways will be exploited and replicated beyond the scope of the project.

Prospects for further research include the overall hierarchy of the identified barriers, regardless of category, the application of other methods for group decision making, or combinations of multicriteria methods to develop a more comprehensive methodological framework, as well as the detection and evaluation of specific solutions for the identified barriers. Furthermore, confidence intervals or margins of errors could be calculated for the assessments. Finally, the implications of the adoption of blockchain technology in specific national contexts could be explored.

Author Contributions: Conceptualisation, I.A., A.P. and V.M.; Methodology, I.A. and A.P.; Writing—Original Draft Preparation, I.A. and A.P.; Writing—Review and Editing, A.P. and V.M.; Visualisation, I.A. and A.P.; Supervision, V.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

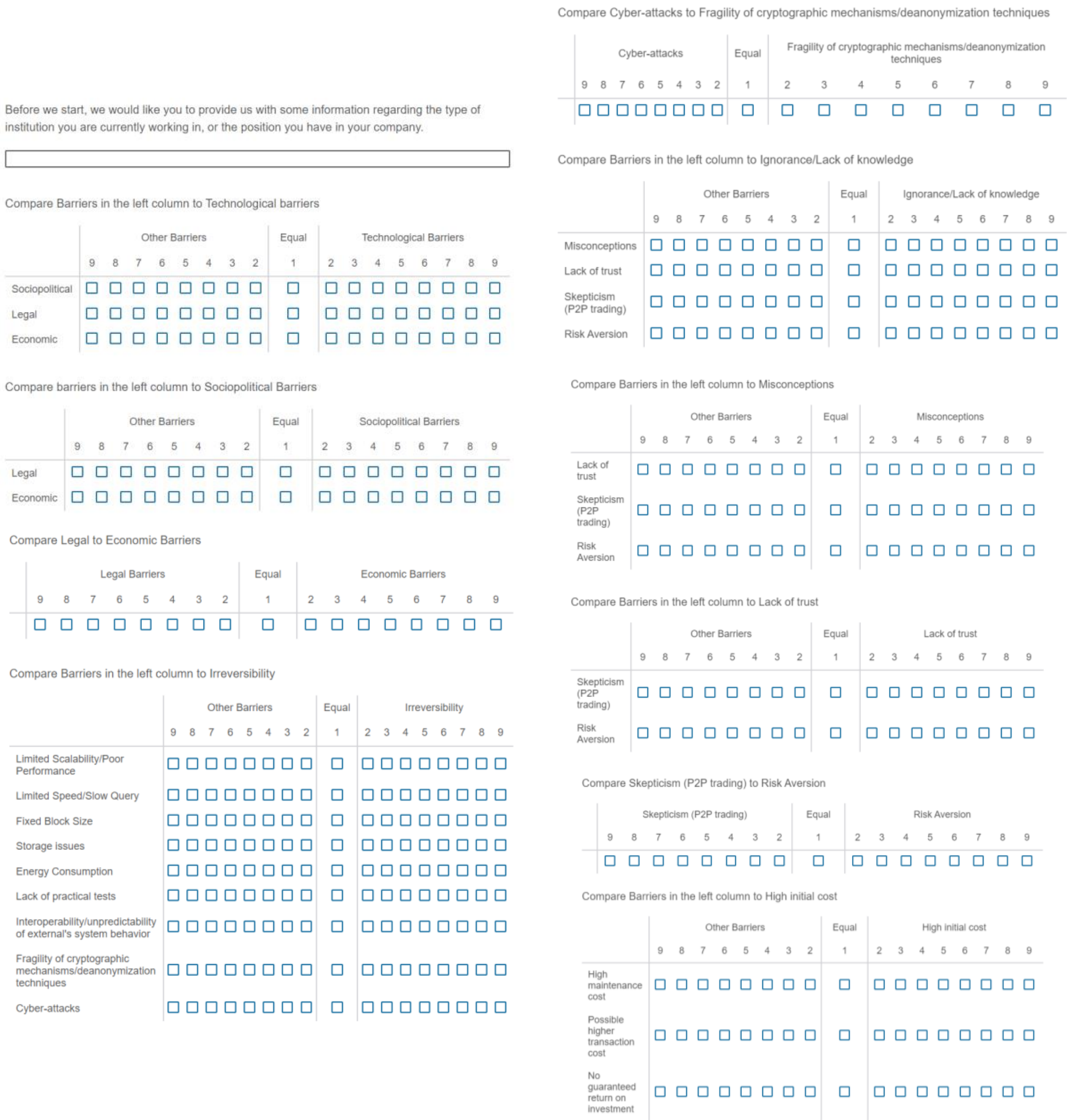
Data Availability Statement: Data is contained within the article.

Acknowledgments: The current paper was based on the research conducted within the framework of the LIFE project "InEExS–Innovative Energy (Efficiency) Service Models for Sector Integration via Blockchain" https://ieecp.org/projects/ineexs/ (accessed on 16 January 2024) Co-funded by the European Union under project ID101077033. The contents of the paper are the sole responsibility of its authors and do not necessarily reflect the views of the EC.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

The survey distributed to decision makers to collect input in order to apply the AHP method and prioritise the barriers of blockchain adoption in the energy sector is shown below:



Before we start, we would like you to provide us with some information regarding the type of institution you are currently working in, or the position you have in your company.

Compare Barriers in the left column to Technological barriers

	Other Barriers								Equal	Technological Barriers							
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9
Sociopolitical	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Legal	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Economic	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Compare barriers in the left column to Sociopolitical Barriers

	Other Barriers								Equal	Sociopolitical Barriers							
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9
Legal	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Economic	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Compare Legal to Economic Barriers

Legal Barriers								Equal	Economic Barriers							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Compare Barriers in the left column to Irreversibility

	Other Barriers								Equal	Irreversibility							
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9
Limited Scalability/Poor Performance	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Limited Speed/Slow Query	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Fixed Block Size	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Storage issues	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Energy Consumption	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Lack of practical tests	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Interoperability/unpredictability of external's system behavior	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Fragility of cryptographic mechanisms/deanonymization techniques	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Cyber-attacks	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Compare Cyber-attacks to Fragility of cryptographic mechanisms/deanonymization techniques

Cyber-attacks								Equal	Fragility of cryptographic mechanisms/deanonymization techniques							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Compare Barriers in the left column to Ignorance/Lack of knowledge

	Other Barriers								Equal	Ignorance/Lack of knowledge							
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9
Misconceptions	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Lack of trust	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Skepticism (P2P trading)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Risk Aversion	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Compare Barriers in the left column to Misconceptions

	Other Barriers								Equal	Misconceptions							
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9
Lack of trust	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Skepticism (P2P trading)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Risk Aversion	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Compare Barriers in the left column to Lack of trust

	Other Barriers								Equal	Lack of trust							
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9
Skepticism (P2P trading)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Risk Aversion	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

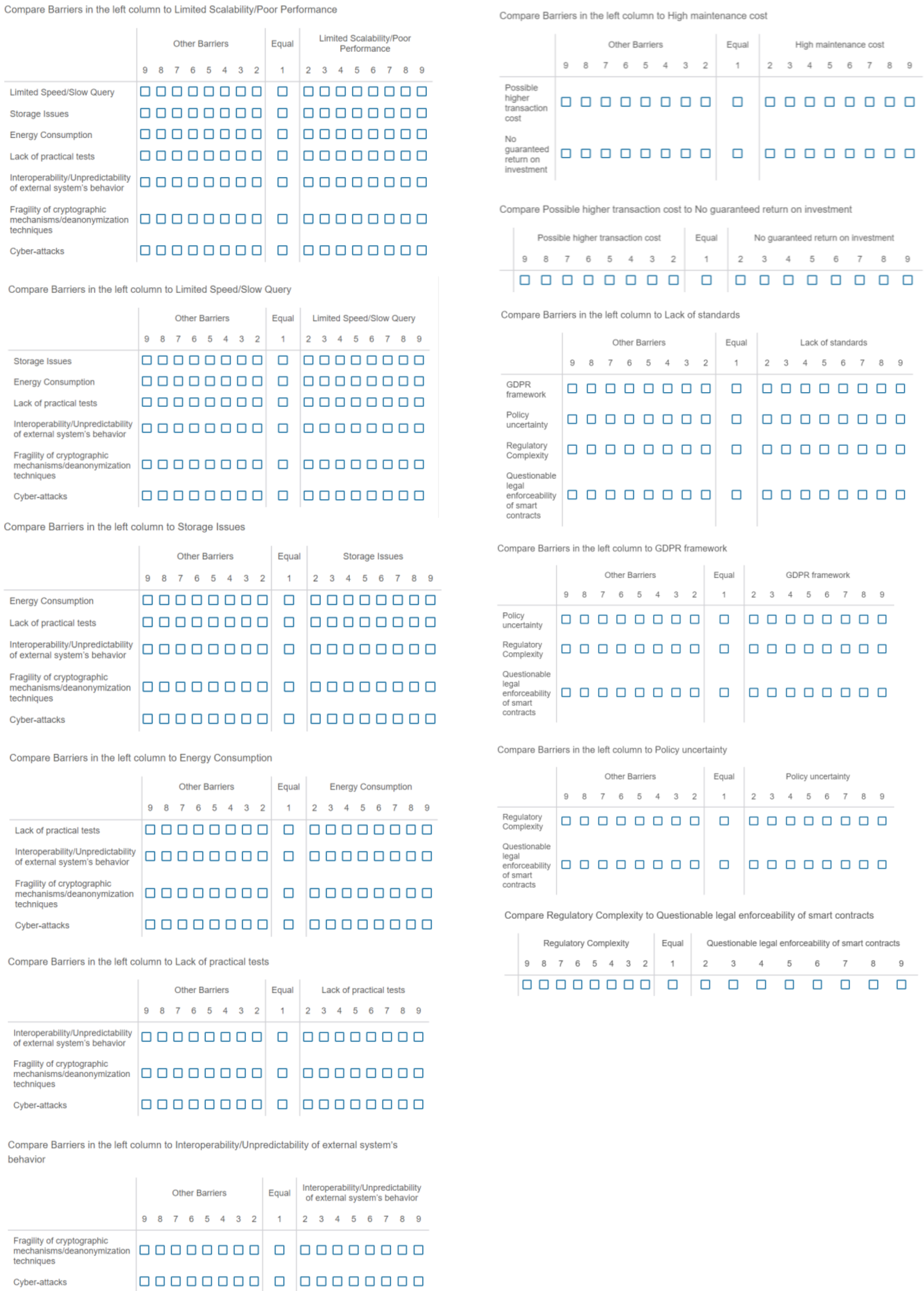
Compare Skepticism (P2P trading) to Risk Aversion

Skepticism (P2P trading)								Equal	Risk Aversion							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Compare Barriers in the left column to High initial cost

	Other Barriers								Equal	High initial cost							
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9
High maintenance cost	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Possible higher transaction cost	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
No guaranteed return on investment	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Figure A1. *Cont.*



Compare Barriers in the left column to Limited Scalability/Poor Performance

	Other Barriers								Equal	Limited Scalability/Poor Performance							
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9
Limited Speed/Slow Query	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Storage Issues	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Energy Consumption	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Lack of practical tests	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Interoperability/Unpredictability of external system's behavior	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Fragility of cryptographic mechanisms/deanonymization techniques	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Cyber-attacks	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Compare Barriers in the left column to Limited Speed/Slow Query

	Other Barriers								Equal	Limited Speed/Slow Query							
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9
Storage Issues	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Energy Consumption	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Lack of practical tests	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Interoperability/Unpredictability of external system's behavior	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Fragility of cryptographic mechanisms/deanonymization techniques	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Cyber-attacks	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Compare Barriers in the left column to Storage Issues

	Other Barriers								Equal	Storage Issues							
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9
Energy Consumption	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Lack of practical tests	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Interoperability/Unpredictability of external system's behavior	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Fragility of cryptographic mechanisms/deanonymization techniques	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Cyber-attacks	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Compare Barriers in the left column to Energy Consumption

	Other Barriers								Equal	Energy Consumption							
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9
Lack of practical tests	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Interoperability/Unpredictability of external system's behavior	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Fragility of cryptographic mechanisms/deanonymization techniques	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Cyber-attacks	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Compare Barriers in the left column to Lack of practical tests

	Other Barriers								Equal	Lack of practical tests							
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9
Interoperability/Unpredictability of external system's behavior	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Fragility of cryptographic mechanisms/deanonymization techniques	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Cyber-attacks	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Compare Barriers in the left column to Interoperability/Unpredictability of external system's behavior

	Other Barriers								Equal	Interoperability/Unpredictability of external system's behavior							
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9
Fragility of cryptographic mechanisms/deanonymization techniques	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Cyber-attacks	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Compare Barriers in the left column to High maintenance cost

	Other Barriers								Equal	High maintenance cost							
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9
Possible higher transaction cost	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
No guaranteed return on investment	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Compare Possible higher transaction cost to No guaranteed return on investment

Possible higher transaction cost								Equal	No guaranteed return on investment							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Compare Barriers in the left column to Lack of standards

	Other Barriers								Equal	Lack of standards							
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9
GDPR framework	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Policy uncertainty	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Regulatory Complexity	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Questionable legal enforceability of smart contracts	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Compare Barriers in the left column to GDPR framework

	Other Barriers								Equal	GDPR framework							
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9
Policy uncertainty	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Regulatory Complexity	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Questionable legal enforceability of smart contracts	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Compare Barriers in the left column to Policy uncertainty

	Other Barriers								Equal	Policy uncertainty							
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9
Regulatory Complexity	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Questionable legal enforceability of smart contracts	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Compare Regulatory Complexity to Questionable legal enforceability of smart contracts

Regulatory Complexity								Equal	Questionable legal enforceability of smart contracts							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Figure A1. Survey template for the collection decision makers' input to apply the AHP method.

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