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Innovative Business Models Towards Sustainable Energy Development: Assessing Benefits, Risks, and Optimal Approaches of Blockchain Exploitation in the Energy Transition

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Abstract

The goals of the European Union towards the energy transition imply profound changes in the energy field, so as to promote sustainable energy development while fostering economic growth. To achieve these changes, the incorporation of sustainable technologies supporting decentralisation, energy efficiency, renewable energy production, and demand flexibility is of vital importance. Blockchain has the potential to change energy services towards this direction. To optimally exploit blockchain, innovative business models need to be designed, identifying the opportunities emerging from unmet needs, while also considering potential risks so as to take action to overcome them. In this context, the scope of this paper is to examine the opportunities and the risks that emerge from the adoption of blockchain in four innovative business models, while also identifying mitigation strategies to support and accelerate the energy transition, thus proposing optimal approaches of exploitation of blockchain in energy services. The business models concern Energy Performance Contracting with P4P guarantees, improved self-consumption in energy cooperatives, energy efficiency and flexibility services for natural gas boilers, and smart energy management for EV chargers and HVAC appliances. Firstly, the value proposition of the business models is analysed and results in a comprehensive SWOT analysis. Based on the findings of the analysis and consultations with relevant market actors, in combination with the examination of the relevant literature, risks are identified and evaluated through a qualitative assessment approach. Subsequently, specific mitigation strategies are proposed to address the detected risks. This research demonstrates that blockchain integration into these business models can significantly improve energy efficiency, reduce operational costs, enhance security, and support a more decentralised energy system, providing actionable insights for stakeholders to implement blockchain solutions effectively. Furthermore, according to the results, technological and legal risks are the most significant, followed by political, economic, and social risks, while environmental risks of blockchain integration are not as important. Strategies to address risks relevant to blockchain exploitation include ensuring policy alignment, emphasising economic feasibility, facilitating social inclusion, prioritising security and interoperability, consulting with legal experts, and using consensus algorithms with low energy consumption. The findings offer clear guidance for energy service providers, policymakers, and technology developers, assisting in the design, deployment, and risk mitigation of blockchain-enabled business models to accelerate sustainable energy development.

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1. Introduction

Achieving energy transition goals has become a key priority, particularly when it comes to European institutions, since tackling the effects of climate change is deemed essential [1]. In order to achieve the clean energy transition, the European Green Deal (EGD) establishes three fundamental principles with the aim of ensuring secure, reliable, and affordable energy supply for the European Union (EU). The principles refer to the development of a fully integrated, interconnected, and digitalised EU energy market; and the prioritisation of energy efficiency, towards the enhancement of the energy performance of the EU building stock, and creation of a power sector, which is based on renewable energy to a great extend [2]. The clean energy transition evidently requires significant changes in generation, transmission, and consumption of energy, with an emphasis on decentralisation, bi-directional flows, energy efficiency, and demand flexibility [3,4].

Despite notable progress in the implementation of clean energy policies, the energy system remains predominantly reliant on fossil fuels [1,5]. Across regions and sectors, barriers of an economic, political, regulatory, technological, and behavioural nature obstruct the uptake of energy-efficiency solutions and hinder the exploitation of renewable energy sources [6,7]. It must also be noted that the market for promoting clean energy products and services is still largely underdeveloped, often due to low levels of consumer awareness, shortage of professional skills, and lack of access to capital [8,9]. But, oftentimes, regulatory barriers delay the development and scale-up of clean energy business models, despite their potential for economic growth and creation of employment [10].

To overcome the great variety of existing barriers, it is crucial to develop new business models and markets for sustainable energy services, adapt and enhance existing business processes and already established value chains, and foster the appropriate conditions for replication of successful cases, while also providing capacity building of market actors to support the clean energy transition.

All market players are affected by the digitalisation of the energy system as interconnected devices, smart meters, and automation increase in adoption [11]. Provisions on digitalisation included through the Clean Energy Package are opening up new business opportunities, in particular, through the new rules on electricity market design and for energy efficiency of buildings [12]. Yet market actors are moving with hesitation (e.g., slow progress in some EU member states to roll out smart meters [13]) when there is increasing innovation offering new tools for disruptive applications [14]. The most prominent example is Distributed Ledger Technologies (DLTs), which are showing promising advancements in ICT for distributing data and controlling transactions in a decentralised manner, with growing use cases in connecting finance, the energy field, and the manufacturing industry, among other sectors [15].

More specifically since the introduction of blockchain by Nakamoto in 2008 in the context of bitcoin [16], the first cryptocurrency, DLTs have gained popularity, and their incorporation in various sectors has been examined [15]. Potential blockchain frameworks have been recommended to support healthcare, the automotive industry, asset tracking, digital ownership, privacy, decentralised identities (DIDs) and identity management, reputation systems, copyright protection, manufacturing, and so on [15,17].

Numerous advantages make blockchain a very promising breakthrough for the energy field. Blockchain-based proposed energy applications include energy trading applications [18,19], management of energy systems [15,18], demand-side management and

demand response [20,21], rewarding mechanisms for local energy production and savings though digital currencies [22], monetisation of behavioural efficiency [23], scheduling of electric vehicle charging and relevant trading platforms [24,25], reporting of buildings energy performance [26] interconnection between smart vehicles [27,28], and carbon trading [29,30]. Blockchain may be a very suitable solution for energy trading applications implemented through the Peer-to-Peer (P2P) model (exchange of energy without the need of an intermediate party), since blockchain-based energy transactions could facilitate the integration of prosumers (participants of the grid operating as both consumers and producers) in energy markets [18,19], while preventing manipulation and frauds in trading schemes (in both electricity and carbon trading) thanks to the transparency offered by this technology [31,32].

Besides energy exchange in smart grids, microgrids, and energy communities, thanks to its decentralised nature, blockchain could contribute to effective energy management despite the complexity of the systems caused by heavy reliance on distributed energy resources [33,34]. Traditional centralised control methods are not successful enough when it comes to smart grid monitoring, supervision, and management. Controlling a distributed energy system centrally may become problematic, particularly when a high percentage of grid users are prosumers [32]. Appropriate, timely and effective demand response can be not only challenging and complicated but also costly. However, a decentralised system can achieve better control and balance between energy generation and consumption [33]. Furthermore, problems caused by potential third-party failure are eradicated [32]. Rewarding and incentivising mechanisms in the context of demand response can also be enabled by blockchain [35].

Blockchain-based platforms, networks, and frameworks can also function and be exploited as databases [36]. This is important for the energy sector, since blockchain can support the safe storage and sharing of energy-related data and metering data [37,38]. Immutability of data, ensuring that blocks stored in the chain cannot be edited or deleted despite remaining accessible, guarantees data accuracy, which is crucial for energy applications, related not only to metering but also tracking of energy consumption, thus allowing consumers to monitor and control their energy mix [31].

It has to be highlighted that systems based on blockchain are generally regarded as highly secure, while reliability is also prioritised, which is significant in energy services [33,39]. For example, ensuring safety and protection, as well as preserving privacy in smart grids pose challenges due to the great number of interconnected smart devices and appliances [31,33]. Decentralised energy systems and smart grids have experienced significant financial losses as a result of malicious attacks and intrusion [40]. Blockchain appears to be an appropriate solution to improve the safety of the smart grid, because user identity is safeguarded through anonymity. Identity management facilitated by DLT ensures that no personal information is revealed, thereby preserving the privacy of network users. In addition, the threat of data leakage by third parties is mitigated, as the necessity for third-party control is eliminated thanks to the use of blockchain [32]. The network's resilience is also reinforced thanks to the availability of data replicas to all nodes [39,41].

Early experience exists in several fields and organisations linked to the energy transformation, where attempts have been made to leverage blockchain to promote efficiency and enhance energy services within pilot projects. However, since blockchain is a relatively new technology, there are still numerous barriers to be addressed and lessons to be learnt to ensure that the incorporation of the technology in the energy field is truly beneficial, effective, and optimal. Previous relevant studies have focused on examining blockchain applications in energy and on identifying risks and solutions [31,42–46]. However, many of the existing studies rely on theoretical frameworks and general use cases, instead of pre-

senting practical application of blockchain-enabled business models and the accompanying risk mitigation strategies. For instance, Ahl et al. (2022) base their analysis on a literature review and expert interviews, through which the potential of new innovative business models exploiting blockchain technology is recognised. Business model opportunities, including Energy as a Service (EaaS), virtual power plants (VPPs), IoT, and energy trading, are mentioned as examples. The design and examination of specific innovative business models exploiting blockchain in the energy sector are proposed as a prospect of further research [31]. Other studies focus on blockchain exploitation on one specific sub-sector of energy applications, such as the 2021 work of Zhou et al., examining barriers of blockchain-based power trading [46]. Therefore, a research gap is identified, and the problem that this research aims to address is the lack of practical recommendations and approaches towards the exploitation of blockchain technology in energy services, since there is a need to provide guidelines regarding the conceptualisation and implementation of energy business models exploiting blockchain, ensuring that key benefits are recognised, and key risks are identified and adequately addressed through appropriate risk mitigation strategies. To this end, this research aims to investigate specific examples of energy services where blockchain can be applied to accelerate the energy transition and focusing on the business models that enable these energy services. These examples are not only theoretically designed; on the contrary, they are actually implemented, and feedback is received from market actors. In this context, the scope of this paper is to examine the successful application of the blockchain in the energy sector through innovative business models, covering a wide range of heterogenous energy services whose implementation is supported by DLT; assess the barriers and advantages of this adoption; and identify mitigation strategies for the risks identified so as to propose optimal approaches of blockchain exploitation. This is achieved by examining the business models of the InEExS project (Innovative Energy Efficiency Service Models for Sector Integration via Blockchain), an EU-funded initiative aiming to explore the tokenisation of energy-related data using a public blockchain with the view to enable and simplify collaboration among market segments and between market actors whose commercial interests are based on the design, deployment, and exploitation of integrated energy services across sectors and energy carriers [47]. Based on the study of the business models, in combination with an examination of the literature review, risks of blockchain adoption in the energy field are identified and assessed through stakeholder consultation with experts directly involved in the deployment of the business models, as well as market actors that have been asked to provide feedback on the business models. Specific mitigation strategies are proposed for the identified risks and, thus, recommendations for the optimisation of blockchain exploitation in energy are provided.

Following this introductory section, which has illustrated the current situation in the energy sector, providing an overview of blockchain applications in energy and describing the scope of the research at hand, this paper is structured as follows:

- Materials and Methods: The second section of this paper demonstrates the tools and the methodological steps followed to identify and propose optimal approaches of exploitation of blockchain in the energy sector through innovative business models.
- Results: Relevant works from the literature, as well as projects and initiatives from the industry, are investigated in the third section. The business models of the InEExS project are described. SWOT analysis for each business model is conducted. Risks of blockchain adoption are recognised and assessed.
- Discussion: The results are discussed, and mitigation strategies for the identified risks, towards optimised blockchain exploitation, are proposed.
- Conclusions: Conclusions are drawn, and potential prospects for further research are presented.

2. Materials and Methods

In this section, the approach and methods used within this paper are described, and the sources of material and data are also mentioned.

The scope of the research at hand is to examine the opportunities and the risks that emerge from the adoption of blockchain in four innovative business models, while also identifying mitigation strategies to support and accelerate the energy transition, thus proposing optimal approaches of exploitation of blockchain in the energy sector. To achieve this, the methodological steps depicted in Figure 1 are followed.

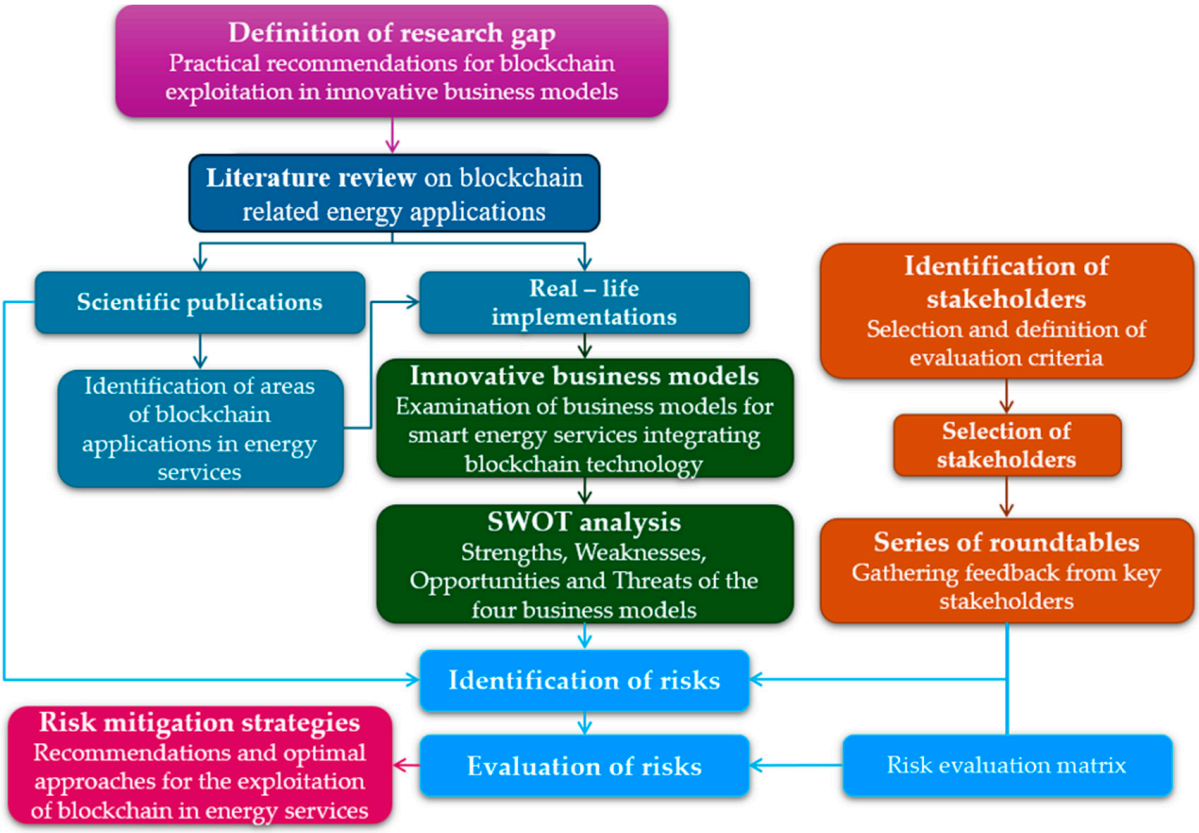

Figure 1. Methodological approach.

The first step is the definition of the research gap, which is the identification of recommendations and approaches to design and implement innovative business models exploiting blockchain to accelerate the energy transition, considering relevant benefits, opportunities, risks, and risk mitigation strategies.

In the second step, the areas of blockchain applications are identified through a review of the most recent and relevant publications, as well as an examination of real-life implementations, including EU-funded initiatives or pilot projects deployed in the industry by companies operating in the energy and ICT sectors. Thus, the EU-funded project InEExS, developing and deploying innovative business models for integration of sustainable technologies across sectors, is furtherly analysed. The sources for the above-mentioned information include various databases of articles, including ScienceDirect [48], ResearchGate [48], Scopus [49], and IEEE Xplore [50], while information about the pilot projects was found on official projects' websites, on relevant websites of the European Commission [51], or on the websites of the organisations that run the projects.

The next step is the analysis of the business models of the InEExS project. In particular, the scope of the project is described, along with the specific objectives it aims to achieve, and the InEExS business models, representing a broad spectrum of blockchain applications

in the energy field, are analysed. The strengths, weaknesses, opportunities, and threats of each business model are highlighted using SWOT analysis. SWOT is a tool developed to address the need for understanding why certain business strategies or plans succeed or fail. It allows organisations to identify the factors that directly influence or shape their future, whether stemming from the internal or external environment [52]. These factors are categorised as strengths (positive internal factors reflecting the current situation), weaknesses (negative internal factors tied to the present), opportunities (positive external factors with potential for the future), and threats (negative external factors that may impact the future) [53]. The primary advantage of SWOT lies in its simplicity, which has made it widely adopted in both the business sector and academic settings. As a methodology, SWOT analysis facilitates strategic planning by leveraging strengths seizing opportunities, addressing or mitigating weaknesses, and preparing for or avoiding potential threats [54]. Examples of the use of SWOT in previous relevant problems are provided in Table 1.

Table 1. Application of SWOT analysis in the literature.

Focus Area	Key Findings	Study
Benefits of blockchain as an alternative to digital payments and cryptocurrency investment business.	With internationally recognized safeguards of confidentiality and the ease of conducting investment transactions and activities without payment, the weaknesses and threats can be controlled for more investors to enter the world.	[55]
Analysis of the economic perspectives of the blockchain technology in agricultural business.	Blockchain technology has big opportunities in agricultural business and agri-food supply chain in the digital economy; however, there is a research gap related to financing the blockchain implementation and cooperation between businesses and the authorities.	[56]
Measurement of the stakeholders' perceptions of the P2P energy trading model using blockchain technology.	The P2P energy trading model using blockchain technology is believed by stakeholders to provide greater benefits to the user community, expand opportunities to consume renewable energy, and contribute to reducing climate change in Indonesia.	[57]
Evaluating the barriers to blockchain adoption in the energy sector using the SWOT and PESTLE tools and the Analytical Hierarchy Process for Group Decision Making.	Main barriers include legal issues, particularly complex regulations, followed by technological security risks, sociopolitical risk aversion, and high initial costs. The SWOT analysis further helped stakeholders provide a comprehensive understanding of the advantages, challenges, and risks involved, and it guided the development of strategies to address these barriers.	[58]
Evaluating the blockchain technology strategies for reducing renewable energy development risks. Integration of SWOT analysis and hybrid MCDM methods in the proposed framework.	The key finding is that blockchain technology can help reduce renewable energy development risks by creating a decentralized energy system, lowering costs, and eliminating monopolies.	[59]
Examination of the current state of blockchain and smart contracts technology in the energy sector, focusing on use cases, key challenges, and potential solutions through SWOT.	The adoption of smart contracts and blockchain in the energy sector offers significant potential for enhancing efficiency, security, and transparency, but successful implementation depends on addressing challenges such as high initial costs, technical complexities, and evolving legal requirements through strategic planning, stakeholder collaboration, and the development of flexible frameworks.	[60]

The data to implement the SWOT analysis were retrieved from relevant documents developed within the InEExS project, from direct communication with the partners involved

in the design and implementation of the four business models, as well as from other official sources, such as databases of scientific papers as described above for the literature review, as well as sources related to national regulations. Subsequently the criteria for selecting stakeholders to participate in the stakeholder consultation process are defined to collect feedback on the business models and on the key benefits and barriers of blockchain exploitation. Therefore, the results of the SWOT analysis are combined with the results of a series of roundtables that were organised in the framework of the InEExS project. The scope of the roundtables was to engage relevant stakeholders and key market actors in order to gather feedback on the development of the business models that are being examined in the InEExS project, the validation of the smart services deployed through the business models, and the replication of the results. The stakeholders' feedback was essential to ensure that the models developed and used meet the needs of both service providers and customers, while also identifying and evaluating the risks of the implementation of the business models and of the integration of blockchain in energy services in general.

The strategy for the identification of the stakeholders to be engaged was based on detecting and prioritising the most important criteria that would determine whether a potential stakeholder's organisation would be suitable for the replication of the business model. To this end, a questionnaire was distributed to the partners of InEExS that are responsible for developing and deploying the business models. According to the results of the survey, the partners aimed to select the replicants based on the six criteria shown in Table 2.

Table 2. Criteria for the identification of potential replicants.

	Criterion	Average Rating
1	Alignment of organizational strategy of the replicant with the developed business model	4.33/5
2	Intimacy level between stakeholder and replicant (collaboration in the past and trust between them)	4.33/5
3	Possibility of further replication of the project's activities and outputs	4.33/5
4	The time frame in which the technologies will be implemented by the replicants	4.00/5
5	Technical capacity (availability of experts) of the replicant to implement technologies	3.83/5
6	Country of the replicant	3.50/5

It is observed that the most important criteria for the selection of the replicants are the alignment of the organization's objectives and strategy with the scope of the business model; the previous collaborations with the stakeholder and the potential replicant; and the possibility and capacity of the organisation to furtherly replicate, promote, and upscale the business models. The stakeholders prioritise organisational alignment because it ensures that the organisation not only has the capacity but also the motivation to adopt and expand the business model. Previous collaboration is also a strong incentive that significantly enhances the possibility of replication, since there is an already established connection and trust between the parties that will also speed up the process. Furthermore, the stakeholders would like to ensure that the replicants have the intention not only to "copy" but also enhance the business model, for instance, by integrating new approaches or broadening the sectoral coverage (e.g., if the business model focuses on the residential sector, it could be adapted to commercial or industrial buildings).

The next crucial element for replication is the time frame, since the business models are highly dependent on the market conditions, which are constantly changing, meaning that

quick replication will increase the chances of success (of course, fast deployment should not be prioritised over careful design and proper implementation). The availability of experts is also important, but not necessary, since the replicants can also cooperate with external partners to be able to deploy the business model. Finally, the stakeholders do not prioritise the country of the replicant as much as the above-mentioned criteria, recognising that they do not need to stick to specific national contexts and that the impact could be maximised if they expand to various countries. However, it needs to be highlighted that the target groups are mostly EU countries.

The stakeholders involved in the consultation process from the identified organisations—potential replicants—represented a wide range of market actors that could be involved in the exploitation of blockchain in innovative business models for energy services to accelerate the energy transition, including energy experts, energy service providers, system integrators, technical and IT experts, technology providers, innovation experts, real estate managers, stakeholders from the public sector, market experts, legal experts, policy experts, and academics.

Based on the results of the previous steps, risks are identified and then evaluated using a risk evaluation matrix. A risk evaluation matrix is a tool used to assess risks based on two key factors: likelihood (the probability that a risk will occur) and impact (the severity of its consequences). This method provides a visual representation of risks, helping stakeholders focus on those that are most critical. Risk assessment matrices are widely used in various sectors thanks to their simplicity and effectiveness in managing uncertainty [61]. Examples of the use of risk assessment matrixes include applications in waste management [62], healthcare [63], health and safety [64], and environmental and energy-related problems [65,66].

Finally, mitigation strategies of the risks are extracted leading to optimal and efficient approaches of exploitation of blockchain adoption in innovative business models towards the digitalisation of energy services are presented.

3. Results

In this section, the results that ensued from the steps described in Section 2 are presented, starting with an overview of blockchain applications in the energy field, and then moving on to the description of the business cases of the InEExS project and the SWOT analysis of each one of their business models.

3.1. Blockchain Applications in the Energy Field

3.1.1. The Blockchain Technology

Blockchain constitutes a digital distributed ledger, whose functionalities consist of storing data as blocks and connecting these blocks by leveraging suitable cryptographic mechanisms. Despite the fact that such data structures are not a new advancement, blockchain technology is quite a novel breakthrough, since it was first defined in 2008 [17]. Recent advances in blockchain systems provide several possibilities for users, allowing them to set up applications decreasing costs and speeding up the deployment of blockchain in various services [67].

The demand for improved quality of blockchain-enabled services poses a challenge to the design of distributed ledger technologies, for example, in regard to the transaction processing throughput [68]. As a key component of a blockchain network, the consensus mechanism directly influences the capacity of transaction processing, the scalability, and the security of the blockchain [69]. A consensus mechanism is defined as a set of rules that all participants in a blockchain network have to abide by. Since blockchain operates as a distributed system without centralised trust, it relies on a distributed consensus mechanism

to ensure that all participants agree on the network's current state [15]. Scalability, on the other hand, refers to the ability of the blockchain network to function properly even when its scale expands. Solutions to the problem of scalability have been discussed in relevant literature in recent years [70].

Some key characteristics of blockchains are presented in Table 3.

Table 3. Blockchain characteristics.

Characteristic	Description
Decentralisation	Traditional centralised transaction systems require validation from a central trusted entity, resulting in performance bottlenecks. In contrast, blockchain eliminates the need for a third-party central trusted agency, since data consistency is ensured by the consensus algorithm [71,72].
Persistence	Transactions are swiftly validated, and honest nodes reject invalid transactions. Once included in the blockchain, it is nearly impossible to delete or rollback transactions. Any blocks containing invalid transactions can be promptly identified [73].
Anonymity	Users interact with the blockchain using generated addresses, preserving their real identities. However, perfect privacy preservation is not guaranteed due to inherent limitations [74,75].
Auditability	Every transaction refers to previously implemented transactions that have not been spent yet. When these transactions are added to the blockchain, their status changes from unspent to spent. This facilitates straightforward validation and the tracing of transactions [74,76].

As explained, blockchain relies on various mechanisms [47] to guarantee its security, immutability, and fault tolerance [77]. Nonetheless, hacks of blockchain systems have been reported, and, as a result, newer blockchain networks need to mitigate ongoing risks [78]. However, as the adoption of blockchain application becomes more and more widespread, several advances are made to ensure confidentiality, integrity, and accountability through blockchain usage [79].

Examples of consensus mechanisms that overcome the hurdles of the traditional Proof-of-Work (PoW) consensus algorithm are the Proof of Stake (PoS) and the Proof of Authority (PoA). According to PoS, the validators, playing a similar role as miners in PoW, need to stake their digital coins. To be rewarded, the validators are designated randomly to generate the blocks, as well as to validate the blocks generated by other participants [80,81]. PoA, on the other hand, is a lightweight algorithm that delivers an effective solution for permissioned blockchains [82]. Instead of implementing the longest chain confirmation rule (like PoW does), PoA leverages on the value of identities. In other words, validators are staking their own reputation instead of staking the digital currency. The number of block validators in PoA is limited, which is beneficial for the scalability of the model, therefore contributing to mainstreaming the adoption of blockchain [83,84].

3.1.2. Classification of Application Areas of Blockchain in Energy

As mentioned in the Introduction, throughout the recent years, the energy field has undergone significant changes, so that decarbonisation can be accomplished. The energy transition is immensely dependent on the digitalisation and decentralisation of energy systems and services. Hence, blockchain can play a crucial role in this transition.

DLT uses in energy have been examined by numerous scholars, while reviews have also been performed to highlight the variety of domains of potential implementations combining blockchain and energy services [45,85,86]. Recent works in the literature have highlighted the major areas of such applications that have been identified. Table 4 provides examples of representative papers and publications for each area.

Table 4. Main areas of blockchain applications in the energy field.

Area of Implementation	Related Publications
Smart grids	[19,20,40,83,84,86,87]
Renewable energy sources	[19,22,59,88–91]
Energy trading	[19,24,92–97]
Energy storage	[98–101]
Electric and smart vehicles	[24,27,28,102–104]
Carbon trading	[29,30,105–108]
Smart metering	[37,38,109,110]

For instance, in [111], the authors perform a detailed review of the incorporated artificial intelligence and blockchain-enabled scheduling, management, optimisation, privacy, and security of the smart grid and power distribution automation [111]. In [91], the authors analysed the current most important issues regarding the combination of blockchain and renewable energy in depth to verify the future development path [91]. In [92], the authors suggest an innovative system that associates cooperative game theory with blockchain technology so as to stimulate users, with the aim of maximising their profit and ensuring secure energy trading [92]. In [98], the authors put forward a communal power synchronised dispatching model based on blockchain, shared energy storage, and demand response, with the aim of reducing costs and the pressure on the grid, while promoting the consumption of clean energy [98]. In [112], the authors examine how data sharing and information technology can support the development of circularity in electric vehicle supply chains and explore the role of blockchain technology to address the circularity needs of battery tracking and capability sharing [112]. In [105], the authors analyse the current situation in regard to carbon trading in China and recognise the relevant future trends and barriers, creating a framework for a smart carbon-trading system based on blockchain towards process optimisation [105]. In [109], the authors propose a distributed and sustainable approach to supervise metering networks, leveraging existing telecommunication facilities, enhancing the implementation and operation, achieving reliability, and reducing costs [109].

Blockchain in energy has not only been examined in the literature but also tested through real-life implementations. Several projects exploiting blockchain in energy services are presented in Table 5.

Table 5. Projects implementing blockchain in energy services.

Project	Use of Blockchain	Areas of Blockchain Exploitation	Source
Brooklyn Microgrid (BMG)	The project enables energy trading through a mobile app acting as a local energy marketplace. Participants purchase local solar energy credits, and excess solar energy is sold via auction.	Smart grids Energy trading Renewable energy sources	[113]

Table 5. *Cont.*

Project	Use of Blockchain	Areas of Blockchain Exploitation	Source
EnergyChain	EnergyChain is based on a private blockchain made to serve energy grid applications; track and notarize utilities data for rebates, certifications, and incentive systems; and even track land, building, and environmental data.	Smart grids	[114]
NRGcoin	The NRGcoin is a rewarding mechanism for green energy, relying on blockchain-based smart contracts.	Renewable energy sources	[115]
SolarCoin	This cryptocurrency is distributed as a reward for solar installations.	Renewable energy sources	[116]
Powerledger	The Powerledger platform enables flexibility and energy trading, combined with traceability of energy use.	Energy trading Smart grids Renewable energy sources	[117]
TwinERGY	TwinERGY empowers citizens and communities to track their energy use and to proactively participate in the market.	Energy trading	[118]
VPP by Sonnen and EWchain	The Virtual Power Plant (VPP) consists of distributed residential energy storage systems, forming a network that is able to absorb excess wind power and therefore preventing limitation of renewable energy by storing wind energy when it is abundant.	Energy storage Smart grids	[119]
Green Energy Wallet	Green Energy Wallet contributes to balancing the grid by connecting EVs and household batteries to a large energy storage system.	Electric and smart vehicles Energy storage	[120]
IBM blockchain	IBM has developed a decentralized platform for trading carbon credits and other environmental attributes.	Emission trading	[121]
Pylon Network	Pylon is a startup that has developed a neutral database based on blockchain to store the users' energy consumption and production data, enabling them to control over their data and to whom they want to share it with.	Smart metering	[122]

Furthermore, the European Commission, in February 2023, launched a regulatory sandbox for innovative use cases involving distributed ledger technologies [123]. The sandbox will annually accept cohorts of 20 blockchain use cases. They will be matched with relevant national and EU regulators for a safe and constructive dialogue on the most relevant regulatory issues. Use cases will be selected based on the maturity of the business case, legal/regulatory relevance, and their contribution to the EU's wider policy priorities. Every year, the most innovative regulator participating in the sandbox will be awarded a prize. The selection and award process will be overseen by a panel of independent academic experts from European universities [124].

While the EU regulatory sandbox initiative represents an important step towards regulatory clarity, especially for novel and decentralised use cases, it is not without limitations. Firstly, participation is selective, meaning that the vast majority of DLT projects in the

energy sector may not have direct access. Secondly, the outcomes of the sandbox are non-binding, meaning regulators are not obliged to act on the insights gained. Additionally, key legal uncertainties (e.g., around GDPR compliance or energy market integration) remain unresolved at scale and depend on future legislative adjustments.

For innovative business models in the energy sector, the EU regulatory sandbox offers valuable exploratory space, particularly when it comes to use cases involving P2P energy trading, data sovereignty, and smart contract automation. However, full regulatory alignment depends on broader structural reforms beyond the sandbox itself, such as adaptations to energy-market rules and data-protection standards.

3.2. Overview of the Business Models and SWOT Analysis

As explained in the previous section, the InEExS project aims to deploy integrated services promoting sustainable technologies through new business models that are applied in real life as specific business cases. In the following section, an overview of the business models is provided, followed by an identification of the most important strengths, weaknesses, opportunities, and threats of each examined model, as recognised through SWOT analysis. The analysis leads to the identification of the main risk categories of blockchain adoption in energy services. The business models are also summarised in Table 6.

Table 6. Business models for innovative energy services.

Business Model	Country	Value Proposition (What?)	Targeted Customer (Who?)	Value Creation/Value Delivery (How?)
Energy Performance Contracting with Pay-for-Performance (P4P) guarantees	Germany	Combing MRV concept with Pay-for-Performance schemes for renovation projects	ESCOs Real estate companies	Smart-metering infrastructure for EV chargers, PV panels, heat pumps. Tokenisation of savings through blockchain
Improved self-consumption on DER in energy cooperatives	Spain	Shared local production of solar energy and optimisation of self-consumption	Energy community (mainly residential sector)	Tokens as rewarding mechanisms to incentivise self-consumption
Energy efficiency and flexibility services for natural gas boilers	Greece	Upgrade of the energy efficiency of heating systems	Retail consumers Energy utilities Natural gas boilers installers	IoT controller connected with legacy heating devices (natural gas boilers)
Smart energy management for EV chargers and electricity-based HVAC appliances	Two locations to be selected (most likely Nordic countries)	Cost reduction of residential charging and heating based on variable pricing, flexibility services on the TSO and DSO levels	Households with interconnected smart appliances EV (charger) manufacturers Heating and cooling manufacturers Energy retailers	Tokenisation of flexibility services, cloud-to-cloud connectivity of distributed energy resources and real time monitoring

In Business Model 1, "Energy Performance Contracting with Pay-for-Performance (P4P) guarantees", the core concept is the deployment of integrated energy services from different sustainable sectors, such as photovoltaic panels, electromobility charging points, heat pumps, and the tokenisation of energy saving data. The main goal is to include in the building renovation contracts Pay-for-Performance guarantees based on the MRV performance indicators determined with help of the smart metering system. The infrastructure of the buildings should be optimised with electrification of the heating system, the energy

efficiency of the system increased, and the overall energy costs reduced. The business model will be implemented in Berlin, Germany.

In this business model, Blockchain technology can be leveraged to manage data generated by smart devices like smart meters. This capability could support the visualization of energy consumption and the calculation of MRV indicators, aiding stakeholders in assessing the performance of updated systems. Additionally, the transparency provided by DLT can enhance the tracking of renewable energy usage. Energy efficiency achievements and comfort levels could also be evaluated through digital P4P contracts. Moreover, blockchain could be exploited to remove the necessity of intermediaries, reduce arbitration costs and prevent losses caused by fraud. In addition, malicious and inadvertent exceptions could be prevented thanks to smart contracts. In addition, tokens could be used to monetise energy savings in smart buildings. As far as MRV exploitation is concerned, meter specific data will be collected in the smart buildings and will be available for the project purpose. These data could be, e.g., DDBB data, meter data, and sensor data, which will be defined and envisaged for use within the MRV framework.

Business Model 1 introduces several benefits for involved parties. More specifically, the contractual schemes based on Pay-for-Performance guarantees are combined with the MRV concept and directly linked to reduction of the energy consumed and, thus, the energy bill. In addition, tenants are encouraged to increase self—consumption of energy locally produced through installed PVs on the building, though it should be highlighted that there might be a lack of economic incentive for the tenants to maximise the consumption of PV power. Furthermore, the sustainable technologies used are more efficient and lead to an overall enhanced performance compared to conventional infrastructure. All the above-mentioned improvements lead to the reduction of the carbon footprint of the real estate companies' portfolio. In addition, the business model has the potential to promote the application of smart digital tools in Germany's residential sector, for instance to identify energy savings potential for apartments and to assist decision making towards optimising the buildings' energy performance. Energy savings, as well as self-consumption, can be rewarded fairly and transparently using blockchain. In addition, blockchain ensures reliability, data accuracy, and immutability, while also preserving privacy. However, potential weaknesses of blockchain must not be neglected, including scalability issues and speed constraints, as well as other risks, such as the irreversibility of transactions and possible mistakes such as data deletion that must also be considered when evaluating business models with blockchain applications in energy services.

The business model can also be supported by the overall external environment and current situation of the energy sector, as there is a general digitalisation trend in energy services [125]. Particularly when it comes to the building sector, the Energy Efficiency Directive [126] and the Energy Performance of Buildings Directive stress the importance of taking measures to improve the energy performance of buildings. The requirements to achieve energy efficiency, reduce energy consumption in the European building stock, and increase renewable energy generation to reach energy transition goals, has been recognised and, thus, innovative business models towards this direction are needed. Furthermore, as expected, several building owners and asset managers are looking to improve the sustainability of their portfolio. On a national level, the ESCO market in Germany is one of the most established in Europe [127]. Therefore, it is likely to explore new markets, trying to gain experience with new digital services. Energy Performance Contracting in Germany tends to be enhanced and combined with demand-side energy efficiency measures into supply-side oriented contracting, and the ESCO market is likely to be furtherly promoted and developed by the anticipated expansion of co-generation [128]. When it comes to blockchain integration in the energy sector, energy industry experts have indicated

through stakeholder consultation processes that blockchain has significant potential to substantially influence the energy sector, thanks to the economic value that the technology promises, based on its advantages, such as decentralisation, transparency, safety, and automation [129]. The attention blockchain has attracted in the German energy industry is also proven by the results of a relevant survey conducted in 2016, which highlighted that, at the time, blockchain was still in the early stages of adoption, but it appeared that there was willingness to test it though pilot projects [130]. In addition, it could be argued that the energy sector in Germany generally encourages business models like Business Model 1. For instance, the Energy Savings Meter Programme in Germany, aiming to leverage digitalisation for the uptake of energy efficiency improvements, was launched successfully [131]. In fact, it has been extended thanks to its success. The programme allows businesses promoting digitally enabled energy efficiency solutions to access public funds [132]. Another example is the Mieterstrom model, offering the building owners the possibility to rent their rooftops to a contractor that will supply sustainable power to the tenant [133]. The German government also provides funding for energy-efficient construction and renovation projects. Loans are also available from commercial banks for newly constructed buildings that exceed the energy efficiency standards [134]. In addition, the rollout of smart-metering infrastructure in Germany is encouraged, but unfortunately, the rollout still progresses slowly [135]. Despite the overall success of the ESCO model in Germany, there are still a few risks and barriers, such as the large upfront costs that the ESCOs must burden to implement energy efficiency projects in buildings and the high payback periods, especially for deep renovation projects [136]. Moreover, the fact that Pay-for-Performance schemes are not as advanced in Europe, especially compared to North America, must not be neglected [137]. Another problem stems from the lack of sufficient legal framework determining the aspects of data availability on blockchain-based applications. The data-protection laws of the EU (GDPR—General Data Protection Regulation [138]) and Germany (BDSG—Bundesdatenschutzgesetz [139]) might pose concerns about the availability of German citizens' data on blockchain platforms, besides the encryption mechanisms and anonymity of blockchain. The difficulties posed by legal and regulatory hurdles with a particular focus in the national environment of Germany have also been detected in previous research [129]. To address this, the business model must ensure that no personal or sensitive data are shared. The lack of established standards to follow as a result of the lack of a well-defined regulatory framework impede the exploitation of the adoption of blockchain in energy services and might inhibit the replication of the business model [58]. Furthermore, despite the safety and privacy preservation of blockchain, security problems, including various types of cyber-attacks, as well as deanonymisation mechanisms, are still considerable threats [39,41]. Those threats, combined with lack of understanding of blockchain and misconceptions, could make involved market actors hesitate to trust blockchain-based systems [41]. The fact that blockchain technology is relatively new in the energy field contributes to this scepticism and uncertainty [31]. The above-mentioned are summarised in the following SWOT analysis (Table 7).

For Business Model 2, "Improved self-consumption on DER in energy cooperatives", households in Crevillent, Spain, will participate in the shared local production of solar energy. The primary objective of this business model is to enhance the PV self-consumption within energy community users by implementing incentivisation mechanisms through the utilisation of tokens. The BC focuses on identifying and implementing the most effective strategies to maximise the benefits and minimise the costs associated with self-consumption for prosumers within energy communities and the broader energy system. The concept of optimised self-consumption of DER involves enabling and helping prosumers to adapt

their energy consumption patterns based on factors such as PV production hours, electricity market price signals, grid conditions, and environmental considerations.

Table 7. Business Model 1: "Energy Performance Contracting with Pay-for-Performance (P4P) guarantees" SWOT analysis.

Strengths	Weaknesses
Reduced energy use and increase in self-consumption	Lack of economic incentive for the tenants to maximise the consumption of PV power
Combination of MRV with Pay-for-Performance	Irreversibility of mistakes in blockchain (e.g., data deletion)
Use of more efficient technology	Scalability issue of blockchain
Reduction of the carbon footprint of real estate companies' portfolio	Limited speed of blockchain
Promotion of the application of smart tools in Germany's residential sector	
Fair rewards for energy savings	
Opportunities	**Threats**
EED and EPBD	Slow roll out of smart meters
Increased renewable production	Lengthy payback ratios for deep renovation
Need for the improvement of the sustainability of the real estate portfolio	High upfront costs
	GDPR
ESCO market in Germany	BDSG
Mieterstrom model	Lack of established standards
Rollout of smart metering infrastructure	Security threats

Smart and P4P contracts can be used for RES use monitoring. In addition, energy tokens could encourage and incentivise self-consumption by rewarding it. Moreover, the DLT platform is used to store the results of the calculations made on-chain by Smart Contracts for Reporting or Verification purposes. The MRV process is applied both off-chain and on-chain. More specifically, hourly consumption data of the energy community members are gathered monthly and processed off-chain, while the energy-savings calculations and performance reporting are performed on-chain.

Business Model 2 introduces several benefits for involved parties. The households participating though the energy community increase the consumption of PV power produced in their municipality, improve energy efficiency, and reduce energy bills. Furthermore, the use of collective self-consumption means that the energy comes from the nearby area saving the energy lost due to the transport of energy. This also means further improvement in energy efficiency and a reduction of CO_2 emissions. In addition, the business model significantly benefits the energy community financially, since the installation investment has a faster payback period. No upfront investment from energy consumers is needed, as the overall solution is provided as a service (AAS) by the energy community. Moreover, the designed incentives scheme and blockchain tools allow for an interactive platform that prompts households to become active participants in the energy system, thus improving the energy literacy of the consumers. Despite the advantages of the business model, there are still a few drawbacks. For example, the possibility that an energy community member decides to leave the community is a risk, particularly with the sharing coefficient for the Spanish self-consumption [140]. In addition, some technical issues of blockchain, including the scalability constraints and performance problems, might hinder the successful adoption of the business model [58].

As mentioned, the general digitalisation trend in the energy sector, especially in the context of prosumer integration in energy markets as part of the overall EU policy towards increase in RES, favour business models aiming to exploit new technologies and deploy integrated energy services. Thus, it becomes apparent that due to the rapid developments

in the energy sector and market, organisations with better knowledge on technological solutions (such as DLT and MRV) are able to adapt to the market needs and requirements. Fortunately, it has been observed that citizens in the EU and particularly in Spain are interested in learning about energy demand and willing to participate in energy communities [141]. Since a new regulation was introduced in October 2018, declaring the right to self-consume renewable electrical energy without charges, several barriers have been addressed [142]. Generally, regulation in both Spain and the EU in general encourages the formation of energy communities (Directive 2018/2001/EU Renewable Energy Directive II (RED II), Directive 2019/944/EU Internal Markets Electricity Directive (IME), Royal Decree-Law 15/2018, Royal Decree 244/2019, Royal Decree 477/2021, Royal Decree 377/2022). These legal frameworks provide definitions and specifications about energy communities, including simplified net billing systems (Royal Decree 244/2019) and incentive programmes for self-producing energy installations (Royal Decree 477/2021). In addition, energy communities in Spain can be supported by various financial instruments, including energy expenditure credits and tax exemptions, as well as non-repayable contributions for pilot projects [141]. In addition, the examined business model is a solution for members of the energy community that are highly affected by variable energy prices [143]. Participants in the energy community may take advantage of reduced energy prices thanks to exclusion from system costs for self-sufficient cooperatives [144]. Moreover, energy community models such as the one deployed by Business Model 2 are perceived as socially beneficial since the social context might also include vulnerable groups [8,141]. It has also been suggested that local energy trading increases the willingness of small and medium enterprises to participate in energy communities [145]. Energy trading can be facilitated by blockchain integration [93]. Despite the overall favourable external environment, it has to be considered that energy communities compete with large electric producers and large suppliers of energy, such as gas suppliers, which provide fossil fuel-based electricity or heat [146]. In regard to the replication of the business models, the time dedicated to administrative processes can be long, as these processes are quite complex [147]. When it comes to technical issues, replicators must be adequately specialised, as deficit of skills and technical expertise can significantly affect the success of the business model. From a financial point of view, although financial incentives exist, access to private investment capital might be limited [148]. Volatility of electricity prices might also result in financial concerns [149]. Finally, when it comes to blockchain, possible threats related to the security of the DLT based system might discourage replicators from digitalising [15]. The above-mentioned information is summarised in the following SWOT analysis (Table 8).

In regard to Business Model 3, "Energy efficiency and flexibility services for natural gas boilers", the case describes how users of legacy natural gas boilers can upgrade their heating systems through a cost-effective IoT controller, while enabling their participation in energy efficiency services to the natural gas supplier. The main novelty of the suggested concept relies on the interlinkage of legacy heating devices with a high energy demand, such as radiators, boilers, and preparation of domestic hot water, to improve the "smartness" of the current and long life-cycle infrastructure of the building. Targeted devices include heating equipment of residential buildings which function through natural gas, adopting diverse control modes. To be more specific, an energy supplier in Greece will provide its retail and clients with smart heating controllers to monitor consumption of gas and electricity, towards the optimization of energy efficiency for space heating, while ensuring user comfort. The offering will also include technical support, fault detection, and maintenance for natural gas boilers. The system is interconnected with a cloud-based energy management system that constantly collects, stores, and analyses the detailed data collected from connected heating devices. The heating controllers are connected the boilers of "pilot" consumers, so as to

allow smart and remote heating control, assessment of gas usage, and communication with cloud energy-management services over Wi-Fi. The user can interact with the upgraded boiler, both through the existing thermostat and the smartphone application, providing climate comfort limits and collecting real-time feedback on the boiler operation. The business model will take place in five Greek cities: Athens, Thessaloniki, Larisa, Trikala, and Volos.

Table 8. Business Model 2: "Improved self-consumption on DER in energy cooperatives" SWOT analysis.

Strengths	Weaknesses
Reduced energy bills for the households. Increase in PV power consumption produced in the municipality. Reduction of energy loss in the electricity system. Increased financial benefits for the energy community. Faster payback period for the installation investment. No upfront investment from energy consumers (AaS). Improved energy literacy of the households. Interactive platform allowing households to be active energy system participants. Blockchain exploitation.	Lack of economic incentive for the tenants to maximise the consumption of PV power. Irreversibility of mistakes in blockchain (e.g., data deletion). Scalability issue of blockchain. Limited speed of blockchain.
Opportunities	**Threats**
Digitalisation trend in the energy sector Need for integration of prosumers in the energy market. Willingness of citizens to participate in energy communities. EU and Spanish regulation on energy communities. New regulations on collective self-consumption. Incentives by national and regional governments. Socially and financially vulnerable groups.	Security threats of blockchain such as cyber-attacks and deanonymisation techniques. Competition of energy communities with large electric producers. Long administrative processes. Lack of understanding or technical expertise. Investment costs. Electricity prices.

The main information used by the blockchain platform is the energy savings achieved, which can be calculated by comparing baseline and actual energy consumption. Baseline consumption is obtained using a machine learning approach. Savings need to be determined by comparing measured energy consumption or demand before and after the implementation of an energy efficiency measure (EEM), making suitable adjustments for changes in conditions. The International Performance Measurement and Verification Protocol (IPMVP) developed a consensus approach to measuring and verifying efficiency investments. The protocol's option D, requiring the application of a Calibrated Simulation model to estimate the baseline performance of each participating consumer, will be followed. In addition, BC2 and BC3 reveal that, besides supporting energy efficient systems, blockchain could encourage behavioural efficiency (e.g., through P4P contracts). In Business Model 3, DLT's decentralisation could be exploited so as to enable cost-effective on-chain transactions through energy tokens.

Business Model 3 benefits end consumers by reducing energy consumption and CO_2 emissions. Non-energy benefits, such as reduction of costs and improvement of thermal comfort, are also caused by the implementation of the business model. Furthermore, the end consumers do not have to be burdened by upfront costs since the solution is provided as a service. Business Model 3 exploits the transparency that blockchain offers so as to track energy consumption while also fostering customer's trust. Moreover, blockchain-based P4P contracts can significantly improve the replication potential of the business model by ESCOs because they facilitate the calculation of the repayment of the overall

investment. The impact of the business model on the portfolios of involved parties is quantified and verified through the calculation of energy savings. The energy-savings calculation can also be useful for reporting purposes, that are of paramount importance to entities that have to prove the energy efficiency they achieve due to established Energy Efficiency Obligations (EEOs). This is applicable to all types of entities participating in the EEOS, such as energy suppliers or grid operators. It is important to highlight that the calculations abide by relevant regulations. As mentioned above, option D of the International Performance Measurement and Verification Protocol (IPMVP) is followed. The MRV approach is also adapted so as to be specifically designed for residential heating applications. Finally, the investment is gradually repaid, with the repayment increasing linearly in correlation with the consumption. Despite all the above-mentioned benefits, a few weaknesses of the business model are also recognised, including technological constraints relevant to blockchain's integration in energy, as well as several difficulties that end consumers that are less likely to be familiarised with user interfaces of mobile applications might face. In other words, navigating through the smartphone application might require technological literacy.

The policy environment of both the EU and Greece favours business models aiming to lower energy consumption in buildings due to the requirements to reach clean energy transition goals [150,151]. The great potential of energy efficiency in buildings to contribute to the sustainable development of Greece has also been recognised and validated in relevant research [152]. The energy transition goals dictate the need to efficiently and transparently track energy use [153]. Furthermore, the overall development and advances of innovative technologies, such as machine learning (used in the context of the business model to simulate baseline energy consumption) or Internet of Things (exploited to interconnect smart appliances), also contribute to a favourable external environment [57]. A few issues exist, regarding the potential concerns of end consumers about the availability of energy and non-energy-related data in the blockchain [154]. Potential participants might hesitate to share their data, especially considering a possible security threat such as a cyberattack [41,154]. The above-mentioned information is summarised in the following SWOT analysis (Table 9).

Finally, Business Model 4, "Smart energy management for EV chargers and electricity-based HVAC appliances", seeks to optimize residential charging and heating to lower costs through variable pricing, minimize CO_2 emissions, and provide grid flexibility services at both the Transmission System Operator (TSO) and Distribution System Operator (DSO) levels. More specifically, smart home appliances over the cloud (API) for the benefit of the consumer, energy company, and the grid. Homes integrated with cloud-enabled appliances (EVs, EV chargers, heat pumps, etc.) in two locations, which will be selected, will take part in this smart home energy management system. Aggregated flexibility is provided to energy companies and grid companies as a service where consumption deviates from the expected profile, while ways to transparently report and compensate this flexibility are also researched.

DLT implementation can support this by leveraging blockchain to reward users with tokens for providing flexibility services while maintaining transparency. More specifically, through blockchain, transparency and trust are ensured in the communication and potential compensation of the deviation from expected "cheapest possible" pattern. The aggregated deviation and provided flexibility will also be communicated to the involved energy company. When it comes to MRV, device-level and home-level energy consumption will be measured in real time, with cloud-to-cloud connectivity to each distributed energy resource. Through an interactive user interface, feedback and inputs on user preferences will also be obtained.

Table 9. Business Model 3: "Energy efficiency and flexibility services for natural gas boilers" SWOT analysis.

Strengths	Weaknesses
Reduced energy use, costs, and emissions for end clients Improved thermal comfort No upfront investment needed (AaS) Improved customer trust through consumption transparency Tracking of energy consumption Verified calculation method of energy savings, approved by regulatory bodies Custom MRV approach for residential heating Gradual repayment	Reduced energy use, costs, and emissions for end clients Improved thermal comfort No upfront investment needed (AaS) Improved customer trust through consumption transparency Tracking of energy consumption Verified calculation method of energy savings, approved by regulatory bodies Custom MRV approach for residential heating Gradual repayment
Opportunities	**Threats**
Digitalisation trends in energy services Energy efficiency potential of the building sector in Greece Need for transparent tracking of energy consumption Development of IoT enabling connection of smart appliances	Security issues and threats Possible hesitance and/or unwillingness of the users to share data

The business model results in several benefits, such as reduction of energy consumption, CO_2 emissions' impact, and electricity costs. On the other hand, self-consumption is maximised. The business model applies to B2C companies that can be benefitted by increased margins in electricity sales and decreased volatility risk on wholesale markets. In addition, new forms of revenue can be exploited, for instance, through demand response. Furthermore, the business model enables new sources of flexibility at the TSO and DSO level. When it comes to blockchain exploitation, despite the advantages of DLT, including transparency, increased trust, and decentralization, technical issues, such as the scalability problem leading to poor performance and limited speed must, not be neglected.

Besides the general digitalisation trend in energy services, the need for efficient and timely demand response has been recognised, and blockchain's potential to support applications related to demand response has been explored by various researchers [98,155,156]. Furthermore, as mentioned in Business Model 3, the development of IoT technology favours the interconnection of smart appliances, which is necessary to achieve the transition towards smart and efficient energy system [77]. The combination of blockchain and IoT has also been studied quite extensively [36,77,157,158]. Moreover, the increasingly widespread use of electric vehicles has also led to the need for smart EV charging services. Many blockchain-based frameworks for smart EV charging have been proposed, including applications relevant to the exploitation of blockchain, in the context of EV battery management, scheduling of charging stations, and payment methods through cryptocurrencies [103,159,160]. Blockchain implementations relevant to electric vehicles have also been investigated in the context of interconnection and communication between smart vehicles (Internet of Vehicles—IoV), connection of vehicles to the grid (Vehicle to Grid—V2G), and energy trading systems for electric vehicles [24,27,156]. However, it must be highlighted that the replication of the business model depends on whether the national framework provides opportunities for variable/dynamic pricing in the energy market. Thus, the scalability of the business model might be impeded if variable pricing is not offered to consumers by all energy companies. In any case, energy trading systems with dynamic

pricing can be supported by blockchain [161]. Finally, similarly to the previous business models, the potential unwillingness and hesitation of participants to share their data due to lack of trust in blockchain and concerns about its security must not be neglected [58]. The above-mentioned information is summarised in the following SWOT analysis (Table 10).

Table 10. Business Model 4: "Smart energy management for EV chargers and electricity-based HVAC appliances" SWOT analysis.

Strengths	**Weaknesses**
Reduced cost of electricity for end customers Maximised self-consumption Minimised CO_2 impact Increased margins (e.g., electricity sales) for B2C companies and manufacturers Decreased volatility risk on wholesale market New forms of revenue New sources of flexibility for TSO and DSO	Irreversibility of mistakes in blockchain (e.g., data deletion) Scalability issue of blockchain Limited speed of blockchain
Opportunities	**Threats**
Digitalisation trend in energy services Need for timely and efficient demand response Need for interconnection of smart appliances Need for smart EV charging services	Possible hesitance and/or unwillingness of the users to share data The scalability of the business model might be impeded if variable pricing is not offered to consumers by all energy companies

Having analysed the four business models, it is useful to conduct a cross-model analysis so as to understand common patterns and differences in diverse use cases of blockchain exploitation in the energy sector, as shown in Table 11. Combing these observations with a categorization of the elements identified, a priority heatmap was generated, and it is shown in Table 12.

The priority heatmap represents categorised risks identified within the SWOT analyses, where if one risk fits more than one category, it is considered multiple times.

Apart from the results of the SWOT analysis, it is important to also consider quantitative metrics to validate the performance, effectiveness, scalability, and replication potential of the proposed business models exploiting blockchain in innovative energy solutions, as shown in Table 13. For the calculation of the indicators, a 10% discount rate was considered.

For the first business model, the calculations are conducted using a starting point of 60 households with an average energy consumption of 7500 kWh per year (based on real data from the pilot implementation of the project). In total, 40% of energy savings are estimated to be achieved as a result of the implementation of BM1. For the replication of the business model, it is necessary to provide an application able to draw data from the installed smart meters, so as to feed them into the blockchain platform, enabling the provision of Pay-for-Performance guarantees. Regular maintenance is needed for the metering infrastructure, while consultations with legal experts are essential to negotiate the terms related to data protection and privacy preservation (applicable for all business models).

Table 11. Cross-model comparison.

Category	Common aspects among business models	Business models where these aspects have greater influence
Strengths	Reduced energy use and carbon footprint	All
	No upfront investment/as-a-service models	BM2, BM3
	Higher self-consumption and cheaper bills	BM1, BM3, BM4
Weaknesses	Limitations of blockchain: irreversibility, limited throughput, scalability	All
	Tenant incentive gap for maximising on-site PV	BM1, BM2
Opportunities	Europe-wide digitisation and prosumer policies (EU Green Deal, EED/EPBD revisions, national energy-community laws)	All
	Rapid rollout of smart devices/IoT	All
Threats	Cyber-security and data-privacy concerns	All
	User scepticism/data-sharing hesitance	All
	High upfront or administrative costs	BM1, BM2

Table 12. Priority heatmap.

	BM1	BM2	BM3	BM4
Political	1	2	0	1
Economic	3	3	1	3
Social	1	3	2	1
Technological	4	4	2	3
Legal	3	1	1	1
Environmental	1	1	1	1
0 = very low priority	1 = low priority	2 = medium priority	3 = high priority	4 = very high priority

Table 13. Quantitative metrics.

Business Model	Estimated Energy Savings on the First Year	Energy Savings by the End of the Project Lifetime (MWh)	Carbon Reduction by the End of the Project Lifetime ($tnCO_2$)	Cost Savings by the End of the Project Lifetime (Euros)	Annual Growth Rate	Project Lifetime (Years)	Net Present Value (Euros)
BM1	365	62,800	25,700 [1]	20,702,000	25%	20	99,500
BM2	825	82,000	21,320 [2]	4,507,900	10%	25	978,750
BM3	4500	341,600	68,320 [3]	11,957,300	20%	15	5,946,300
BM4	2520	647,500	32,375 [4]	123,023,000	30%	15	16,694,000

[1] Considering a conversion factor of 0.41 $kgCO_2$/kWh according to "https://www.umweltbundesamt.de/en/press/pressinformation/co2-emissions-per-kilowatt-hour-of-electricity-in (accessed on 18 June 2025)". [2] Considering a conversion factor of 0.26 $kgCO_2$/kWh according to "https://www.miteco.gob.es/es.html accessed on 18 June 2025)". [3] Considering a conversion factor of 0.2 $kgCO_2$/kWh according to "https://www.designingbuildings.co.uk/wiki/Carbon_emissions_of_electric_heating_v_gas_(1). (accessed on 18 June 2025)" [4] Considering a conversion factor of 0.05 $kgCO_2$/kWh according to "https://www.carbonfootprint.com/docs/2019_06_emissions_factors_sources_for_2019_electricity.pdf. (accessed on 18 June 2025)".

For the second business model, the calculations are conducted based on an energy community whose members (5500 residential units) have an average consumption of 3000 kWh per year. In total, 5% of energy savings are estimated to be achieved as a result of the implementation of BM2. For the replication of the business model, it is necessary

to provide a mobile application guiding users to optimise their self-consumption and connecting the production and consumption data to the blockchain platform in order to tokenise energy savings. Regular maintenance is needed both for the PVs and storage installations and the metering infrastructure.

For the third business model, the calculations are conducted based on a consumer basis of 2500 households (starting point) with an average consumption of 9000 kWh a year (for heating). In total, 20% of energy savings are estimated to be achieved as a result of the implementation of BM3. The replication of the business model requires the existence of compatible natural gas boilers; the operation and maintenance of the smart heating controller; and the connection with the app, which provides measurement and verification with the blockchain platform to store data.

For the fourth business model, the calculations are conducted based on a starting point of 2400 beneficiaries—households with an average consumption of 7000 kWh. In total, 15% of energy savings are estimated to be achieved as a result of the implementation of BM4. EV chargers, PVs, and/or home batteries are needed to replicate the business model, using the energy management system enabled by blockchain.

For all business models, the economic performance, as well as the replication and scalability potential, depends on the national context. For instance, hardware affordability, digital literacy, and energy infrastructure readiness need to be considered, especially in developing countries. More specifically, different equipment is necessary to implement each business model. BM1 and BM2 need smart metering infrastructure, making the business model hardly applicable in countries where the smart meter rollout has been delayed. However, the potential of energy communities in developing countries should be considered, since they can reduce dependency on the grid, increase autonomy, and mitigate energy poverty. BM3 can be replicated easily in multiple national contexts since the only existing infrastructure necessary is the natural gas boilers, and the hardware and software costs are relatively low. The infrastructure requirements are more complex when it comes to BM4, making its replication in developing countries more challenging. For all business models, a certain level of digital literacy from the side of the consumers is necessary so that they are able to handle and exploit the web or mobile applications that facilitate them in optimising their consumption; however, it needs to be highlighted that capacity building can help overcome such challenges (for instance, in the current implementation of the business models, senior citizens without great familiarity with digital systems have also been able to participate).

To furtherly highlight the unique value proposition of the presented business models, it is worth comparing them with previous applications of blockchain in energy services. There are several applications related to smart grids and particularly local microgrids and energy communities (therefore related to BM2). A famous example is the Brooklyn Microgrid, connecting households in Brooklyn [113]. In many of these network applications, energy management plays a significant role, with a focus also on demand response (related to BM4, especially when the solutions include connectivity with smart devices and flexibility for the grid), such as the DEDALUS project, offering blockchain-based solutions to preserve privacy, ensure trusted data governance and sovereignty, and enable energy flexibility and data sharing with the aim of deploying effective algorithms and services for residential demand response [162]; the BRIGHT project, deploying community-enabled ways for engaging consumers in demand response [163]; and Powerledger, offering grid stability and flexibility services [117]. Energy trading applications exploiting blockchain are also popular, as a multitude of related models have been created, and many platforms aim primarily at integrating prosumers and small producers into both local and larger markets. As expected, such applications are often combined with implementations related to smart

grids. However, blockchain transactions in networks are not limited to energy trading. On the contrary, DLT has also been tested for data management and sharing, as well as for privacy protection, which touches upon all the BMs of InEExS—particularly BM1 and BM3. Examples of blockchain enabled trading include Powerledger [117], SunContract [164], PLATONE [165], PARITY [166], and FEVER (which also includes flexibility trading) [167].

Regarding energy storage, the approaches are limited and usually combined with other applications. Nevertheless, there are several models related to charging EVs (relevant for BM1 and BM4), the most common application of blockchain in electromobility, such as TwinERGY, which provides the TwinEV module that allows electric vehicle charging in public and private charging points considering grid restrictions [118], and SENDER, enabling smart-charging energy management system exploiting the flexibility capabilities of electromobility [168]. When it comes to emission trading, the solutions are often combined with the management of other certificates related to renewable sources, such as Guarantees of Origin (GoOs). These guarantees certify whether the energy consumed, for example, by an organisation, comes from conventional or renewable sources. This is very useful for companies that want to monitor their environmental footprint, since they have the ability to control their energy mix (e.g., Tal.Markt [169]). Additionally, applications related to smart meters involve data management through blockchain (related to BM1 and BM3). An example is Prosume, an energy data management blockchain-based platform [170].

Finally, approaches related to renewable sources are quite widespread, especially concerning solar energy (related to BM2). Moreover, various cryptocurrencies or tokens are included in the examined applications of blockchain in energy. These might be used for energy trading, as well as to reward prosumers for their energy consumption and production patterns (for instance, self-consumption can be rewarded, similarly to BM2; SolarCoin is an example [116]). Another application enabled by blockchain is the funding of energy efficiency-related projects through crowdfunding platforms (for instance, SunExchange, a crowdfunding platform for small-to-medium-scale solar projects in developing countries, allowing investors worldwide to help fund plants with national currency or bitcoin payments [171].

Therefore, it is observed that the InEExS business models combine approaches observed across various applications and aim to maximise impact by using efficient technologies and ensuring positive environmental and social impact.

3.3. Identification and Qualitative Assessment of Risks of Blockchain Adoption

To assess and evaluate blockchain adoption in energy projects and particularly within the InEExS business models, we have examined and combined the risks presented in the relevant literature and identified through the SWOT analyses of the business models, and we have organised the most important risks. The risks could be divided in the following categories (based on the PESTLE framework—Political, Economic, Social, Technological, Legal, and Environmental [58]):

Political: Since the technology is relatively new, political institutions might not have enough knowledge around blockchain technology so as to fully be aware and understand the possibilities and benefits of its exploitation and adoption in energy-related applications. This lack of knowledge and awareness also leads them to ignore practical aspects, thus not being able to estimate the actual feasibility of specific blockchain use cases [41]. In addition, insufficient understanding of a new technology inevitably leads to uncertainty and hesitance, that is to say, the applications of blockchain could be considered as high-risk, making the technology's exploitation in energy services more difficult [31,172]. The correlation of the political environment with the success of a use case aiming to integrate blockchain in energy services is also observed through the examination of the business

models of the InEExS project. For instance, the applicability of blockchain-based processing of metering data in Business Model 1 relies on national and EU policies on smart metering rollout in Germany. In Business Model 2, EU and national policies on energy exchange and trading within smart communities directly affect the potential of a decentralised blockchain-based energy generation tokenization framework. When it comes to BC4, the scalability and replicability of the business model in various countries is dependent on national policies on variable pricing in energy markets.

Economic: Blockchain, as an emerging technology, involves significant establishment and maintenance costs, because skilled service providers and professionals are needed to incorporate it in energy implementations [32,41]. This could increase hesitance for potential stakeholders that would like to invest in blockchain, because of the lack of secure payback, meaning that substantial return on investment is not certain [33,41,154]. For instance, the high establishment costs of blockchain could negatively impact the replication potential of Business Model 1, because renovation projects are already associated with high upfront costs and long payback periods. Especially when it comes to medium or small businesses operating in the energy sector, the investment might not be feasible, due to the intense computational requirements of blockchain forcing them to update the hardware of their existing resources [33,41]. Moreover, the companies might need to allocate their financial resources in legal consulting services to help them comply with the regulation, which has not yet been fully formulated and clearly outlined [33]. In addition, it is not completely clear if DLT will reduce or increase the transaction cost in energy-related implementations [32]. More specifically, it has been argued that the reduction of transaction fees, the prevention of failure in transactions, and the elimination of control by third parties thanks to blockchain's decentralised functionality will result in an overall reduction of transaction cost [173,174]. Blockchain has also been proposed as a solution to reduce cost in EV's charging applications. On the other hand, the energy use during transactions may rise, thus increasing the cost. However, since there are methods and consensus mechanisms that reduce energy use of blockchain, this risk can be easily mitigated. Therefore, the influence of blockchain on transaction cost depends on the specific application and the characteristics of the examined use cases [32].

Social: When it comes to the general public, there is not enough knowledge surrounding blockchain, because the technology is relatively new, and its functionality is quite complex. This lack of awareness results in misconceptions and a limited understanding of blockchain [41,175]. Additionally, society often perceives new technologies as unreliable [31,33,41]. As a result, potential blockchain applications may be overlooked due to a tendency to avoid risks [41,172]. For instance, many potential prosumers might be hesitant when it comes to participating in decentralized P2P energy trading schemes, an observation that is very relevant to Business Model 2. Decentralization of energy exchange and integration of new technologies in the process might be perceived as too risky, as the security of the trading system might be questioned [154]. Furthermore, there is a possibility that the algorithm enabling the energy transactions could favour specific participants of the grid in the early stages of its deployment [31,154,176]. Additionally, society might be sceptical about decentralized energy management though blockchain. Decentralization might be perceived negatively, since several participants feel safer if the system is managed by an external unit and would not easily trust an entirely digitalized system without an alternative of external control [154]. Society is also concerned about the security of the system and its reliable function. Data sharing through blockchain is another application that makes potential participants sceptical, as they will likely feel uncomfortable to share energy-related data [31,154,176]. Security concerns are a common risk across all four examined business models.

Technological: Many challenges arise from the novelty of blockchain technology. For example, insufficient practical tests have been conducted to validate its efficiency and functionality in non-financial applications [31,41]. Researchers have also highlighted scalability issues with blockchain [31,32,154]. As the scale expands, the technology may struggle to function effectively due to the increased workload, which can lead to reduced performance. Furthermore, data storage becomes problematic in large-scale blockchain systems since all nodes store a record of transactions. This requires managing vast amounts of data in a large network. Additionally, a fixed block size may pose challenges as the scale grows, potentially causing the speed of request submissions to exceed the block generation speed [31]. Overall, blockchain's limited speed is a significant obstacle [32,39]. This is particularly observed when DLT-based platforms are used as databases, a challenge known as "slow query" in the literature [31]. In the examined business models, blockchain is utilized to store data; thus, the problem of slow query is notable. Another technological challenge is the issue of irreversibility. The permanent nature of blockchain can lead to problems such as data deletion and other errors, which are difficult to correct [41]. For instance, an incorrect transaction cannot be undone, and the result of a faulty smart contract cannot be altered [41,154]. This is particularly important in business models where decentralised energy exchange is enabled by blockchain. Although distributed ledger technologies are generally regarded as secure, they are still vulnerable to cyber-attacks [39,41,154]. Another potential challenge is the future fragility of blockchain's cryptographic mechanisms. As cryptography and quantum computing progress, current blockchain protocols may become susceptible, potentially exposing data stored on the blockchain, as encrypted data are replicated across all nodes in the network [39]. Nevertheless, these developments are likely still decades away. Additionally, the anonymity provided by blockchain could be at risk, as deanonymization techniques have already been identified [41].

Legal: From a legal perspective, the regulatory framework about blockchain implementations in energy services appears to be insufficient [33,41]. Subsequently, uncertainty is observed, and there is a perceived complexity around specific matters. For instance, legal vacancies may result in concerns about the availability of users' data in the blockchain, especially considering legal frameworks such as the EU General Data Protection Regulation [39,154]. Particularly in Business Model 1, the strict regulatory framework of Germany in regard to data protection makes the exploitation of blockchain even more challenging. In addition, the legal aspects of smart contracts have not been sufficiently analysed, and the legal enforceability of digitalized blockchain-based contracts is questionable, since there is no use of legal language and terminology to ensure the validity of the contractual agreement [39,154]. Thus, there might be uncertainties about legal aspects of P4P contractual schemes used in Business Models 1 and 3. Another crucial risk is the lack of standardisation, which is due to the fact that blockchain applications have increased only in recent years [39,41]. For instance, there are no specific guidelines that legal experts and advisors should follow to resolve conflicts relevant to blockchain, such as mistakes in transactions, which are relevant for all examined business models and especially Business Model 2. Another example of a risk of legal nature is the lack of standards that can be followed towards the interoperability of blockchain with other facilities [39,41,177].

Environmental: The main concern in this category of risks is the environmental impact of blockchain's energy consumption caused by computationally intense consensus algorithms, such as Proof of Work (PoW). The use of such algorithms is important because they contribute to the system's security and integrity, they ensure the honesty of the users, and they guarantee the validation of the transactions. Especially considering the energy sector, where business models integrating blockchain aim to maximise positive environmental impacts and minimise energy consumption, the energy intensity of blockchain cannot be ne-

glected. However, several alternate consensus algorithms have been developed, requiring significantly less energy to be executed [31,41].

The level of the identified risks' categories is assessed based on two pillars (see Table 9):

- The probability of the risks' occurrence, expressed through three probability levels: UNLIKELY, MODERATE, and VERY LIKELY.
- The estimation of the risks' impact, expressed through three impact levels: LOW, MEDIUM, and HIGH.

The estimation of the risk level was conducted in the framework of the InEExS project through a two-fold stakeholder consultation approach. More specifically, as a first step, the probability of the risk occurring in the examined business cases was estimated by external stakeholders, with whom the InEExS business models were discussed. The leaders of the InEExS business cases invited relevant key stakeholders to participate in roundtables with the aim of co-examining the business cases and providing insights and perspectives on the market's situation, needs, and constraints.

In total, 22 bilateral and multilateral meetings were held within the period from November 2022 until October 2023, with 95 stakeholders participating in total from all the business cases (Table 14).

Table 14. Stakeholder consultation meetings.

BC	No. of Meetings	No. of Participants	Type of Stakeholders
1	6	12	Energy experts, real estate managers, legal experts, and technical experts.
2	5	26	IT experts, legal experts, energy experts, technology providers, public sector, Art. 7-obligated parties, and academia.
3	6	30	Public sector, energy experts, technology providers, real estate managers, and academia.
4	5	27	Energy experts, energy services providers, system integrators, technology providers, public sector, and investors.

Within these external stakeholder consultations, it was considered that the political risks are of moderate probability, since despite the general risk aversion, the need to combat the climate crisis drives political institutions to promote policies that favour the integration of sustainable technologies. For example, initiatives like the European Green Deal and the U.S. Inflation Reduction Act actively promote clean energy and digital innovation, reducing the likelihood of policy resistance. The probability of economic risks to appear, on the other hand, is very likely, especially when it comes to high upfront costs and maintenance costs. For instance, installing smart meters, integrating DLT infrastructure, or maintaining peer-to-peer energy trading systems can involve substantial capital and operational expenses. Therefore, whether the business model will be replicated largely depends on the potential of the business model to result in financial and environmental benefits, so that potential investors are willing to provide financial resources to replicate it. As far as social risks are concerned, the probability of them occurring was estimated as moderate by the external stakeholders. While lack of trust in DLT is likely to occur, such as concerns about privacy, transparency of algorithms, or the perception of blockchain as being associated with cryptocurrencies rather than energy solutions, there are also numerous market actors that need to actively participate in innovative business models encouraging sustainability and energy efficiency. Examples include community energy cooperatives, local prosumers, and municipal utilities embracing digital energy marketplaces. As expected, the probability

of technological risks to occur is very likely, since blockchain is a novel innovative technology that has not yet been fully adapted to the needs of the energy sector. This includes integration challenges with legacy grid infrastructure, latency issues in high-frequency energy trading, or scalability limitations for large, distributed networks. Finally, external stakeholders assessed the probability of environmental risks occurring as unlikely, because the energy intensity of blockchain has sufficiently been addressed thanks to the development of consensus mechanisms requiring low power draw to enable transactions. For example, Ethereum's transition from Proof of Work to Proof of Stake reduced its energy use by over 99%, making DLT applications significantly more sustainable.

As a second step, the impact of each category of risks was estimated in the InEExS project through an internal stakeholder consultation procedure. That is to say, participants in the deployment of the InEExS business cases were asked to evaluate the impact of the six different factors. According to the internal consultation procedure, the impact of political, societal, and economic risks is medium. While these three factors may pose some concerns, they can still be addressed fairly easily. Technological risks, on the other hand, have a very high impact on blockchain integration in energy services, because if the reliability, security, performance, and efficacy of the system are not sufficient, the business model will most likely not be replicated. The InEExS partners has also recognised that legal risks are of high impact and can even completely inhibit aspects of the business model form being implemented. Finally, despite the unlikelihood of environmental concerns appearing in the business models, the impact of the environmental factor is considered medium, since the overall goal of the business model is to result in positive environmental benefits. The risk assessment scale is explained in Table 15 and the results are shown in Table 16.

Table 15. Risk assessment scale.

	IMPACT		
	LOW	**MEDIUM**	**HIGH**
PROBABILITY			
VERY LIKELY	LOW	MEDIUM	EXTREME
MODERATE	LOW	MEDIUM	MEDIUM
UNLIEKLY	LOW	LOW	LOW

Table 16. Risk-level estimation results.

Risk Description	**Probability**	**Impact**	**Risk Level**
Political	MODERATE	MEDIUM	MEDIUM
Economic	VERY LIKELY	MEDIUM	MEDIUM
Social	MODERATE	MEDIUM	MEDIUM
Technological	VERY LIKELY	HIGH	EXTREME
Legal	VERY LIKELY	HIGH	EXTREME
Environmental	UNLIKELY	MEDIUM	LOW

4. Discussion

The analysis of the business models and the identified risks prove that implementing blockchain in energy services requires thoughtful design to ensure it is both truly beneficial and financially viable. Moreover, many barriers must be addressed, making the development of a viable and effective methodology essential.

Political aspects: To ensure that political risks of an innovative business model integrating blockchain in energy services are mitigated, the business model should be aligned with national and EU-level plans regarding energy efficiency, improvement of energy performance, reduction of energy consumption, and increase in renewable energy generation. For instance, Business Model 1 exploits the policy recommendations of the EU towards improvement of the energy performance of the European building stock, as well as national policies of Germany, such as the rollout of metering infrastructure. Business Models 2, 3, and 4 also involve households as end consumers and therefore align with EU's policies to reduce consumption in the residential sector, while Business Model 2 is also favoured by national policies on energy communities. It has to be recognised that political risks go beyond policy alignment, as they also have implications for power dynamics and vested interests. Blockchain solutions providers should thus play by the rules and respect established political realities if they are to be successfully adopted.

Economic aspects: To mitigate economic risks of blockchain exploitation in innovative business models, the economic environment and conditions of the country must be thoroughly analysed. Such conditions may refer to taxes' volatility and variable energy prices. For instance, Business Model 2 facilitates prosumers affected by the volatility of energy prices. Generally, the economic feasibility of the business models should be assessed to reduce financial risks. For instance, as far as Business Model 1 is concerned, high upfront costs and payback ratios are expected for energy efficiency projects in buildings, especially when deep renovation is considered. Thus, to ensure that blockchain-based Pay-for-Performance contracts for renovation projects are an attractive investment; financial KPIs such as payback time, net present value, internal rate of return, and return on investment should be estimated. Revenue streams, cost structures, and cash flows should also be analysed. Furthermore, it should be emphasised that the improvement of the building's energy performance leads to economic benefits not only through cost savings emerging thanks to energy savings, but also because of the increased asset value of energy efficient properties. Another approach to mitigate economic risks, ensuring that financially and socially vulnerable groups can also be benefitted by the business model, is the thorough research and investigation of potential economic incentives or financial aids offered by the EU, national government, or regional authorities, especially in regard to energy communities. Finally, alternative financing schemes (e.g., as a service, deployed in Business Models 2 and 3) can alleviate barriers related to high initial costs, as no upfront investment is needed.

Social aspects: When possible and applicable, business models should emphasise social, non-energy benefits (ease of use, climate comfort, and environmental benefits), while also trying to increase profits for vulnerable groups. As mentioned, Business Model 2 aims to take this into account. The potential of business models integrating blockchain in energy services manages to address issues related to energy poverty and social inclusion should be emphasised so as to increase chances of overcoming social risks. In particular, business models focusing on the exploitation of blockchain in microgrids and energy communities can facilitate the energy access for consumers in remote areas that are hard to reach. Moreover, by improving energy efficiency in buildings, Business Models 1 and 3 have the potential to ensure healthy indoor living environments in terms of temperatures, humidity, and noise levels, as well as air quality. Improved indoor environment can also lead to enhanced productivity, particularly in case of replication of the business models in office buildings. According to the International Energy Agency, energy-efficiency improvements can even improve mental well-being, since it has been demonstrated that chronic thermal discomfort can negatively affect mental health [178]. In addition, all examined business models are likely to be affected by the lack of trust in blockchain technology, while Business

Model 3 mainly targets technologically savvy end clients because they need to be able to understand the functionality of the mobile application and interact with the user interface to visualise energy use and energy savings. To ensure that potential replicators and target groups who are not aware of blockchain technology and its benefits, and consumers that are less familiar with new technologies, are not excluded from the business model, capacity-building activities need to be organised. These educational activities should adequately explain the overview of blockchain and its applications, as well as the processes of the business model, in a simplified manner. This will allow stakeholders and participants with various backgrounds to understand the technologies. An explanation of both internal and external factors of the business model should be provided, so as to sufficiently inform involved parties about the context of the energy field and the need for decentralisation, increased penetration of renewable sources in energy systems, participation of prosumers in energy markets, and provision of flexibility services. For instance, potential replicants and participants of Business Model 4 need to be adequately familiarised with the concepts of demand response and flexibility provision, so as to comprehend how they can be supported by blockchain. Therefore, each business model should be able to extract and present a strong value proposition that will emphasise how the business model satisfies the needs of the market and convince participants. Capacity-building activities could effectively alleviate misconceptions, battle hesitance, and increase trust in new sustainable technologies. Furthermore, such activities should be organised as interactive sessions when possible, so that the business models can be enhanced and enriched based on the received feedback.

Technological aspects: As expected, technological risks are estimated to have a very high impact, as well as high probability of influencing the application of business models exploiting blockchain in energy services. One of the highest priorities in such business models should be the security of the system. Security can be guaranteed through systems of intrusion detection to prevent cyber-attacks. Additionally, data-protection impact assessment plans can be implemented, investigating the impact of a potential intrusion, in terms of the data that will be exposed. Security can also be reinforced through the use of hybrid blockchain models, as has been explored in previous research [179]. By integrating the strengths of both private and public blockchains, hybrid systems offer a balanced solution that **enhances** security, transparency, scalability, and efficiency. For instance, the use of hybrid blockchain has been suggested in smart grids and microgrids, P2P energy trading, electric vehicles, and combined electricity and carbon trading [180–183]. The advantage of hybrid models in energy applications is the fact that sensitive data such as energy usage patterns and transactions can be protected using the identity verification and access-control features of private blockchains (e.g., Hyperledger Fabric). Meanwhile, information that benefits from public scrutiny—such as grid performance, energy mix, and carbon footprint—can be handled via a transparent public blockchain (e.g., Ethereum). This approach not only enhances trust among stakeholders but also improves operational efficiency and reduces costs compared to fully public blockchains, since the computational requirements are reduced.

In regard to the overall system's reliability, backup plans and processes must be considered to ensure that the functionalities of the system will not be jeopardised. The blockchain framework should be harmonised with suitable existing, updated, or novel infrastructure such as smart meters, photovoltaics, EV chargers, and heat pumps, and it should be coordinated through the partnership of multiple domains (energy domain, technological field, and building and transportation sectors). The interoperability of physical and ICT infrastructure should be carefully examined. Moreover, simulations and tests before the actual implementation of the business model, if applicable, can assist technical experts in

the detection of potential problems beforehand. In addition, blockchain platforms used in energy services should be specifically tailored for, or adapted to, the needs of the energy sector, adequately addressing scalability, speed, and latency issues. For example, the exploitation of blockchain in the InEExS project Business Models 1–4 is enabled by the Energy Web (EW chain) platform. EW chain is a public blockchain based on Ethereum and uses Proof of Authority (PoA), tailormade for energy applications [184]. The platform serves as a shared intermediary for all involved parties. Its potential applications encompass digital and smart contracts that can monitor renewable energy consumption and participation in flexibility services; store energy and non-energy data; visualize energy usage; manage Pay-for-Performance (P4P) contracts based on energy efficiency or comfort improvements; issue energy tokens to encourage self-consumption; and automate the quantification and verification of energy savings. Additionally, the EW chain could facilitate on-chain transactions, standardized energy efficiency reporting, and authentication and authorization mechanisms, which are the main challenges of all the business models.

- **Blockchain platform:** More specifically, the platform Energy Web (EW Chain) [2] is the world's first open-source enterprise blockchain platform tailored to the needs of the energy sector. As mentioned, the EW-chain is a PoA public blockchain derived from Ethereum blockchain technology, ensuring low energy consumption and efficiency. Since it is EVM-based, solidity can be used to materialise the business logic of each business model into a new smart contract. The Decentralized Data Exchange (DDEx) service supports high-volume, low-latency on-chain transactions, and the DID-based authentication and authorization mechanism provides for trusted and secure participation in energy transactions. The EW chain can be scaled up to support any energy-related use case and will be employed to record the output of all energy service transactions. EW Chain has extremely low transaction costs, stemming from its low instantaneous power draw that is about 7.5 kilowatts, with 50 validator nodes spread across the globe. In comparison, Ethereum draws roughly 1,000,000 times more power, and Bitcoin consumes roughly 2.2 million times more power than EW Chain.
- **Smart Contracts service:** The Smart Contracts generator follows the factory contract [185] pattern ["https://research.csiro.au/blockchainpatterns/general-patterns/contract-structural-patterns/factory-contract/, accessed on 18 June 2025"] and allows for increased security during the contracts generation, legal compliance and interoperable reporting of energy KPIs. The currently existing paper-based Service Level Agreements (SLAs) for meeting energy KPIs will meet their digital twin on the EW chain, moving closer to legally binding smart contracts. This bridging between the off-chain physical agreement and the on-chain smart contract will enforce secure storage and execution of the SLAs as well as the auditability of historical transactions related to the legal contract and the contract itself in an interoperable fashion. It is important to note that while InEExS contracts aim to enhance transparency and legal clarity, the legal enforceability of any contract, ultimately depends on the jurisdiction in which it is subject to interpretation and enforcement—in our case the InEExS business cases.
- **Tokenisation service:** extension service of the EW Chain, which has already been deployed in commercial applications to allow token holders to pay for decentralized application services, by using the native cryptocurrency of the EW Chain that is the Energy Web Token (EWT). Within InEExS, EWTs will also be used to tokenize the verified savings and flexibility as contribution of participants in energy services transactions.

Based on Figure 2, it becomes apparent that the blockchain platform is the central enabler of the energy services provided by the business models. It must be highlighted that the potential of the platform to bring together diverse market actors, ranging from

technology providers to energy service companies and real estate managers, is a key factor to the success of the business models.

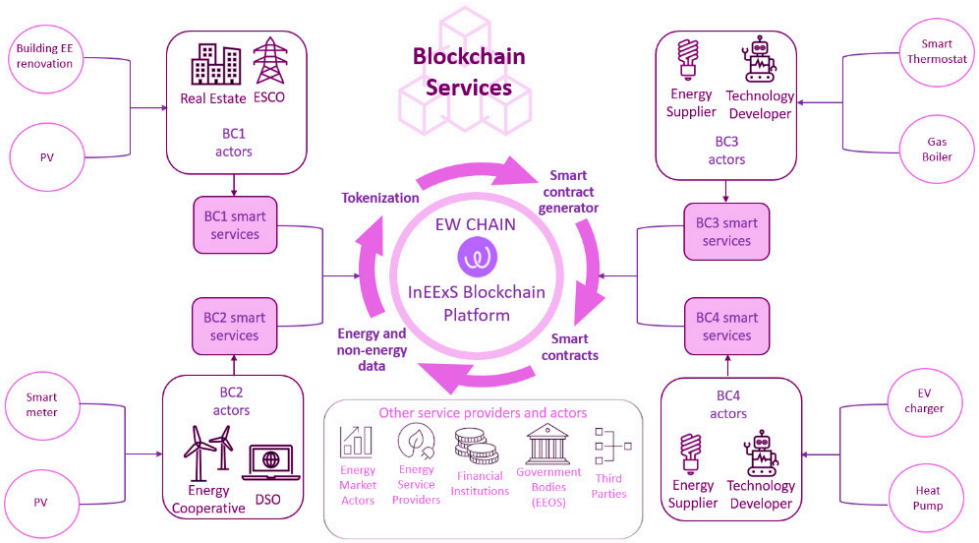

Figure 2. Integration of services of the business cases (BCs) through the blockchain platform.

It is also noteworthy that several additional mitigation strategies can be explored to address the scalability issue of blockchain, including techniques such as chain pruning, which is used to remove or reduce parts of the chain if the system can function properly without them [186]. Blockchain compression is another mitigation strategy for blockchain's scalability and performance issues, since by reducing the size of data stored in individual blocks, it becomes possible to decrease storage and bandwidth needs while maintaining the integrity and functionality of the blockchain [187]. Additionally, the problem of limited blockchain scalability can be addressed through the sharding technique, which is enabled through the division of the blockchain into sections for parallel processing [188]. Sidechains can similarly improve blockchain's scalability by running parallelly to the main chain, allowing assets and data to be transferred between them [189]. The aforementioned techniques can be combined with effective consensus algorithms, such as the Proof of Stake (PoS), which eliminates the computational race of PoW, because users with a larger stake (ownership) in the digital currency have a higher chance of validating transactions [190]. All of these solutions can be applied in various energy services enabled by blockchain, but the specific characteristics of each application should be carefully examined. For instance, chain pruning could lead to data availability issues [191]. Block compression may introduce computational complexity and thus resource consumption, as nodes must compress and decompress data [192]. Potential security vulnerabilities and consistency issues across the blockchain network can be caused by sharding [193]. Sidechains may introduce complexity to the system in terms of interoperability [189]. Finally, the fact that nodes with significant stake holdings can exert disproportionate influence over the network when PoS or PoA is used introduces a threat to the decentralised function of blockchain [194].

Legal aspects: Despite the recent entry into force of MiCA (Regulation (EU) 2023/1114) and the adoption of the Data Act (Regulation (EU) 2023/2854) [195]), the regulatory landscape for distributed-ledger solutions in the energy sector is still evolving at the union level. A careful examination of national regulatory frameworks, as well as EU regulation for EU member states, needs to be conducted for all aspiring business models. The examination should focus on data storage, sharing, and processing; token issuance; and the new smart-contract requirements introduced by the Data Act.

The first layer of risk stems from the data-protection law. Since the emergence of blockchain, it has been difficult to reconcile the ledger's immutability with data subjects' rights under the GDPR, most notably the right to erasure (Art. 17) and storage limitation (Art. 5-1-e). For instance, in Business Model 1, significant risks have been identified as an implication of Germany's data-protection law. Consultancy with legal experts is required or advised to ensure compliance with regulation. Since the emergence of blockchain, it has been difficult to define the boundary between personal and non-personal data due to the technical ability to deduce information about individuals from seemingly unrelated data points. The April 2025 EDPB Guidelines 02/2025 clarify that full GDPR compliance is required whenever personal data—even merely hashed or pseudonymised—are written to a chain [196]. Practically, three technical–legal design patterns are recommended: (1) keep personal data off-chain and record only cryptographic commitments, (2) use strong pseudonymisation or zero-knowledge proofs to avoid disclosing raw meter data, and (3) incorporate key-shredding/crypto-archiving or a Data-Act-conform "kill-switch" so that data can be rendered unintelligible if erasure is requested.

The enforceability of smart contracts is another point of contention. The Data Act (Articles 30–36) now mandates (1) access-control mechanisms, (2) auditability, and (3) a safe-termination function for any contract that automates data sharing [197,198]. These requirements can be met with upgradeable-proxy patterns or time-locked kill-switches without negating decentralisation. Civil-law enforceability further relies on contractual information compliant with the Consumer Rights Directive [199], off-chain terms evidencing offer and acceptance; a qualified electronic signature is needed under eIDAS 2.0 (Regulation (EU) 2024/1183 [200]) if form requirements apply. Very relevant to online identity, the forthcoming EU Digital Identity Wallet will allow household prosumers to sign metering data and selectively disclose only the attributes needed for settlement, thereby reducing the personal-data footprint. This is further supported by the Data Act, which confirms that users—not device manufacturers—own the data generated by connected appliances. In this way, significant progress can be made towards consumer-respecting data sharing in demand-response (DR) and Pay-for-Performance (P4P) schemes

National and EU regulations should also be studied to identify potential incentives for participation in energy communities, DR programmes, or P4P schemes. The SWOT analysis of Business Model 2 already noted that Spanish energy communities were paralysed until Real-Decreto-ley 15/2018 [201] and Royal Decree 244/2019 [202] lifted the so-called "sun tax" and legalised collective self-consumption. Likewise, Germany's 2024 Solar-Paket I [203] and the ongoing amendment of the Energiewirtschaftsgesetz introduce new remuneration streams for flexibility services.

Finally, lack of standardization, which is due to the fact that blockchain exploitation in energy is generally a new concept, must be considered. This is particularly important in business models 3 and 4 since blockchain is expected to "cooperate" with other smart appliances through appropriate APIs. In this context, it is important to also consider the para-regulatory role of technical standards. While technical standardisation is essentially driven by technical stakeholders, such as engineers and scientists, its para-regulatory status and functions deserve to be examined from a sociological and legal perspective as well [204,205]. A number of organisations have contributed to the technical standards of blockchain, including the European Committee for Standardisation (CEN) and the European Committee for Electrotechnical Standardisation (CENELEC) [206], through the CEN-CLC/JTC 19 (Joint Technical Committee 19) "Blockchain and Distributed Ledger Technologies" [207], which was established based on the recommendations presented in the CEN-CENELEC White Paper on "Recommendations for Successful Adoption in Europe of Emerging Technical Standards on Distributed Ledger/Blockchain Technologies" [208].

The JTC has been working closely with ISO/TC 307 "Blockchain and distributed ledger technologies" [209]. Another notable advancement of the International Organisation for Standardisation (ISO) towards the standardisation of blockchain is the recent publishment of the second edition of the "Blockchain and distributed ledger technologies—Vocabulary" ISO 22739:2024 [210]. In addition, the International Telecommunication Union Telecommunication Standardisation Sector (ITU-T) has also contributed to blockchain standardisation through Focus Groups (pre-standardisation, such as "Application of DLT (FG DLT)", "Digital Fiat Currency (FG DFC)", and "Data Processing and Management to support IoT and Smart Cities & Communities (FG DPM)") and Study Groups (formal standardisation, e.g., SG13 "Cloud computing requirements for blockchain as a service (BaaS)", SG16 "DLT and e-services", SG17 "Security aspects for DLT", and SG20 "Blockchain of things") [211]. Other contributors in the framework of blockchain standardisation include the Institute of Electrical and Electronics Engineers (IEEE) [212], the StandICT—EU Observatory for ICT Standardisation [213], and the European Telecommunications Standards Institute (ETSI, specifically the Industry Specification Group on Permissioned Distributed Ledger (ISG PDL)) [214]. Technical standards for blockchain cover a wide range of topics, such as interoperability for seamless data exchange and communication between different blockchain protocols and platforms, governance, identity frameworks, security of the different nodes, networks and services, and safe smart contracts [215]. Thus, they provide a structured framework for integrating blockchain into complex energy systems. These standards not only enable innovation but also address governance challenges, particularly in areas where traditional regulatory bodies may be slow to respond [205]. Furthermore, it becomes clear that the interdisciplinary nature of blockchain standardisation calls for the inclusion of socio-legal expertise throughout the development process [216].

Environmental aspects: To mitigate environmental risks, blockchain platforms with low energy consumption should be used, relying on consensus mechanisms that are not as energy-intensive as Proof of Work. Instead, energy-efficient consensus mechanisms should be used, such as Proof of Stake and Proof of Authority. In Business Models 1–4, Proof of Authority is used, guaranteeing not only low consumption but also minimized transaction cost. The overall environmental impact of business models exploiting blockchain should also be assessed, examining specific key performance indicators, such as energy savings and CO_2 abatement. Recent work furtherly highlights the fact that the environmental footprint of a blockchain depends on how consensus is reached, rather than on the ledger itself. PoW, which was used in Bitcoin, is notably energy-intensive due to the need for computationally expensive mining processes. In fact, according to recent works, Bitcoin's demand is currently at more than 150 TWh per year—comparable to the annual electricity use of a whole country—which is translated into 70 Mtn CO_2 emissions and significant e-waste from high-turnover mining hardware [217,218]. On the other hand, PoS, adopted by Ethereum, drastically reduces energy consumption by over 99%, as it eliminates the need for mining by relying on validators, removing the need for competitive hashing [219]. The power draw is reduced from ~0.41 GW to <1 MW, and independent modelling of multiple PoS chains confirms electricity use that is three-to-five orders of magnitude below Bitcoin [220]. PoA further minimises environmental impact by relying on a limited number of pre-approved validators, reducing both computational and energy requirements [218]. However, a complete assessment of blockchain's sustainability must also consider the full life-cycle impact of blockchain-enabled systems, including node hardware production, maintenance, disposal (e-waste), and network communication energy. Introducing a life-cycle analysis framework would enable a more holistic evaluation of the environmental footprint across different blockchain architectures and deployment scenarios, particularly in IoT contexts. The above-mentioned mitigation strategies are generally aligned with

previous research: For instance, Liu et al. (2022), examining the application of blockchain technology on smart sustainable energy business models, highlight the urgent need for continuous policy support [221]. Bürer et al. (2019), investigating use cases of blockchain in the energy industry, mention the possibility of businesses becoming more receptive of new alternatives of financing models that support decentralised energy production and the systems needed to distribute energy in a heavily distributed energy exchange configuration, based on blockchain adoption [33]. Lastly, Zhou et al. (2021), analysing barriers of blockchain adoption in power trading, propose mitigation strategies, including standardisation, preliminary design, large demonstration projects, and policy and regulation support, among others [46].

Policy recommendations: Based on the analysis of mitigation strategies for the risks related to blockchain exploitation, the following policy recommendations are extracted:

(1) Standardisation of grid integration frameworks for renewables and distributed energy sources, involving the creation of national frameworks for integrating renewables and DERs into the grid, ensuring uniform rules for feed-in tariffs and clear guidelines for P2P energy trading through blockchain technology.
(2) Development of GDPR-compliant energy data platforms, involving the creation of secure, interoperable blockchain-based platforms for energy-data sharing that comply with GDPR while enabling real-time optimisation.
(3) Providing consistent support for energy communities by ensuring legal recognition and providing administrative and financial support for energy communities, while also promoting energy efficient behaviour and self-consumption optimisation through blockchain exploitation.
(4) Updating building regulations by revising national building codes to mandate retrofits for energy efficiency and provide financial incentives for compliance that can be combined with P4P guarantees enabled through blockchain.
(5) Enabling demand response and consumer-compensation mechanisms by establishing clear national frameworks and blockchain-based compensation mechanisms for consumer participation in demand-response programs.
(6) Balancing natural gas transition policies by incorporating interim support for improving natural gas systems during the transition to renewable energy.

5. Conclusions

The research at hand focuses on the analysis of four business models deployed by the EU-funded project InEExS, integrating blockchain in energy services: “Energy Performance Contracting with P4P guarantees”, “Improved self-consumption on DER in energy cooperatives”, “Energy efficiency and flexibility services for natural gas boilers”, and “Smart energy management for EV chargers and electricity-based HVAC appliances”. By applying the SWOT market analysis tool, it becomes apparent that several benefits are included in the business models and few weaknesses are identified, and when it comes to the external environment, it is important to consider both the national and EU policies and frameworks. The weaknesses and threats that emerge from the SWOT analysis and stakeholder consultation are not limited to technological issues; instead, they expand in the political, economic, social, legal, and environmental scope. Technological and legal issues are estimated to have the highest level of risks, followed by social, economic, and political factors that are assessed to be of medium risk. This observation aligns with existing studies, such as Malhorta et al.’s 2022 study, which prioritises the legal and technological risks in the effort to guide businesses with regard to blockchain adoption [222]. Diestelmeier (2019) stresses the importance of forming policies and regulatory frameworks to support DLT implementation [18]. Moreover, according to surveys distributed to potential prosumers in

the framework of the research of Borges et al. (2021), the reluctance of blockchain adoption is mainly due to the regulation and legislation uncertainty [154]. Furthermore, previous research such as a study by 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, highlighting the need to address the exploitation of blockchain in the energy sector as a multifactorial problem [31]. In contrast with Ahl et al.'s work, the study at hand expands the scope of examining different perspectives of stakeholders by integrating the evaluation of the identified risks through the risk evaluation matrix and by proposing specific mitigation strategies. The importance and influence of technological risks are also recognised in the relevant literature, since many studies have attempted to map the technical constraints of blockchain adoption across sectors [41,46,223]. According to the results of our study, environmental matters are expected to be at the lowest level of risk. Specific mitigation measures to overcome legal risks include investigation of the regulation, consultancy with legal experts, abidance by data-protection requirements, standardisation of procedures, and consideration of the para-regulatory role of technical standards. To reduce technological risks, the development of intrusion detection systems, preparation of data-protection impact assessment plans, establishment of backup processes, implementation of simulations and tests, and adaptation of blockchain frameworks to the needs of the energy industry are recommended. The political risks can be alleviated through alignment with policies and respect of established political realities. Economic risk mitigation can be implemented by analysing the economic environment and conditions, assessing the economic feasibility of the business model, calculating relevant indicators in advance, considering the impact of the business model to asset values, investigating potential economic incentives, and exploring alternative financing schemes. From a social perspective, risks can be managed by emphasising non-energy benefits, ensuring social inclusion, and conducting capacity-building activities. Finally, the use of non-energy-intense consensus algorithms and calculation of environmental indicators can alleviate environmental risks.

The conclusions of this research may have significant implications for various stakeholders involved both directly and indirectly in the exploitation of the adoption of blockchain in innovative business models in the energy sector. More specifically, focusing on the identified legal and political risks, policymakers can identify issues that hinder blockchain technology from being widely used in energy services. Furthermore, energy service providers, varying from energy retailers to grid operators and utilities, can use this study as a reference point to effectively design and implement business models integrating blockchain. Furthermore, they can take the assessment of risks into account to prioritise the mitigation strategies that are more important. Blockchain developers and other technology providers and experts in the ICT sector may also benefit from the study, focusing on the risk mitigation strategies proposed from a technological point of view. This research is useful not only for stakeholders involved in the exploitation of blockchain in energy services, since the methodology of the study can also be replicated by other researchers aiming to examine opportunities, benefits, and risks, and propose risk mitigation strategies and optimal approaches for the exploitation of several technologies in various sectors.

It has to be recognised that this research at hand also presents a few limitations. Firstly, the SWOT analyses consider the national context of the business models, which were tested in specific EU countries, limiting generalisability to regions with differing regulatory frameworks or energy infrastructures. Different circumstances may need to be considered in case of replication of the business models in other countries. In addition, further research could also focus on broader sectoral coverage, such as industrial applications or cross-

border energy trading and emission trading. Finally, the results are qualitative and subject to the perspectives of the stakeholders involved in the roundtables. Therefore, the potential bias of the stakeholders should not be neglected.

Prospects of further research include actual implementation of the risk mitigation strategies in business models, so as to assess their utility on a practical basis and furtherly develop them into practical solutions. Besides their applicability in the proposed business models, the mitigation strategies could also be tested within the framework of the replication of the models, so as to test the scalability of those strategies. Furthermore, based on the results of the implementation and in-field validation of the four business models described in this paper, best practices could be identified and complement the risk mitigation proposals to formulate even more comprehensive optimal approaches of blockchain exploitation in energy services and innovative business models. Additionally, the risk assessment could focus on the specific identified risks instead of their categories, including visual representation of the likelihood and severity of each risk, so as to improve the prioritisation of mitigation strategies. Finally, performance metrics and adoption rates from existing blockchain projects could be compared to the results of the implementation of the examined business models to improve the quantitative assessment of the overall impact. A graphical summary of the research is provided in Figure 3.

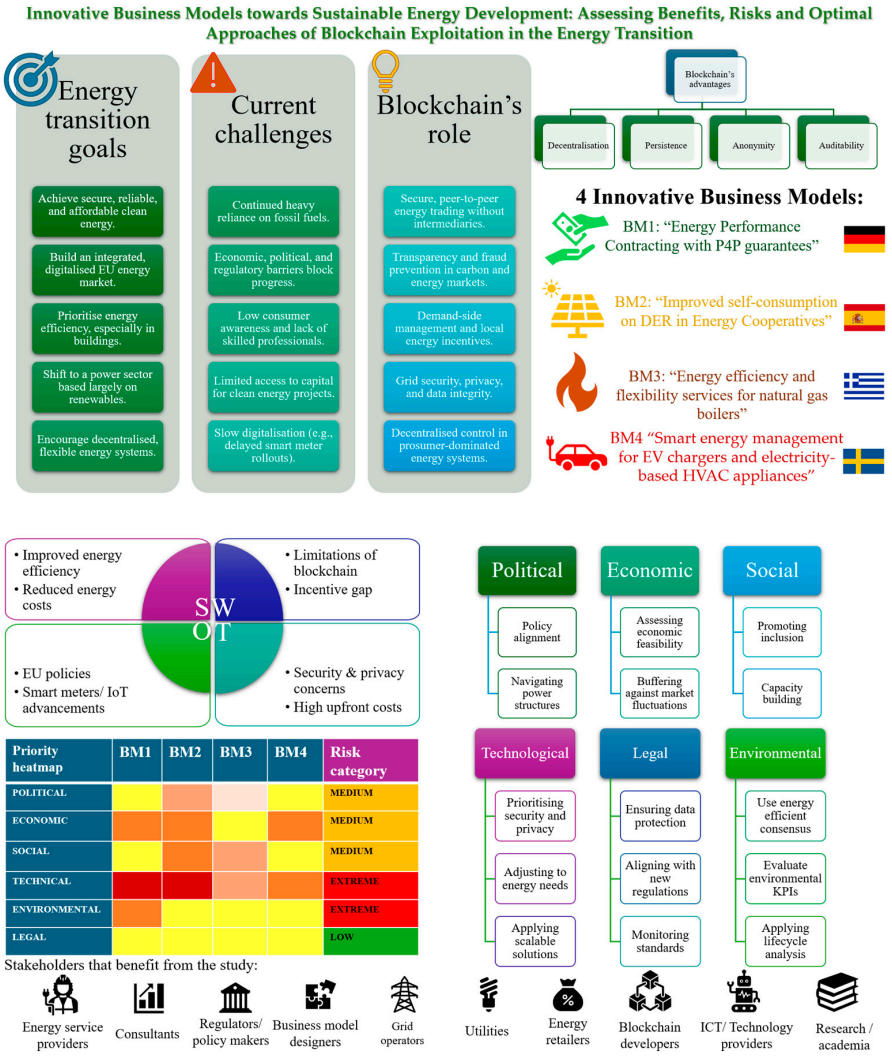

Figure 3. Graphical summary.

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