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Distributed Ledger Technologies for the Energy Sector: Facilitating Interoperability Analysis

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ABSTRACT The use of distributed data storage and management structures, such as Distributed Ledger Technologies (DLT), in the energy sector has gained great interest in recent times. This opens up new possibilities in e.g. microgrid management, aggregation of distributed resources, peer-to-peer trading, integration of electromobility or proof-of-origin strategies. However, in order to benefit from those new possibilities, new challenges have to be overcome. This work focuses on one of these challenges, which is the need to ensure interoperability when integrating DLT-enabled devices in energy use cases. Firstly, the use of DLTs in the energy sector will be analyzed and the main use cases will be presented. Then, a classification of DLT-Energy use cases will be proposed. Secondly, the need for a common reference architecture framework to analyze those use cases with a focus on interoperability will be discussed and the current activities in research and standardization in this field will be presented. Finally, a new common reference architecture framework based on current activities in standardization will be presented.

INDEX TERMS Blockchains, distributed ledger, distributed power generation, microgrids, renewable energy sources, standardization, systems architecture, virtual power plants.

I. INTRODUCTION

THERE is a great need to modernize our current energy system to enable integration of new technologies and to adapt to an increasing complexity of the information exchange. This modernization will require also upgrading grid and market processes and applications. Integrating new components such as distributed energy resources or advanced metering systems into current market and grid processes poses new challenges, requiring a new way of thinking about, for example, current data storage and management structures. The emergence of Distributed Ledger Technologies (DLT), as distributed data storage and management structures, has opened up new possibilities in this field, but also presented new issues. Those issues were identified in [1] and classified in 5 different groups: Security, privacy and identity; Interoperability and standards; Data access, liability and markets; Fairness and acceptance and; Scalability and sustainability. The present paper focusses on giving solutions to promote and ensure interoperability of DLT-enabled devices in energy use cases.

This work will provide an overview of what distributed data and information storage for the energy sector mean and what use cases are involved. Then, it will explain what a reference architecture is and why it is needed to approach the topic of energy use cases with distributed data and information storage. Furthermore, it will justify the need for a common architecture reference framework to analyze and compare these reference architectures with focus on interoperability. At the end it will propose a new common architecture reference framework, based on the current activities in the international standard organizations.

Although the concept of distributed data storage structures in the Information and Communication Technologies (ICT) sector is clearly defined, in the energy sector there is always some confusion between the words decentralized and distributed. For example, when talking about distributed generation, one may assume, that those energy resources belong also to a distributed data storage and management structure, while in reality it is often referring to decentralized structures in opposition to a centralized one. Therefore, before going further, a clarification about what the authors mean by distributed data storage structures and why they are important in the energy sector is needed. The topic of distributed data storage and management structures is rather wide and the authors shall make no attempt to review all the relevant literature here. Rather, we only attempt to provide a context useful for understanding the problematic of the analysis of energy use cases which are based on distributed data storage structures.

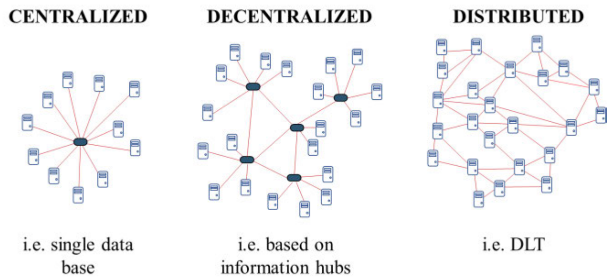

FIGURE 1. Simplified ICT structures of data storage. The data flows are marked in red.

Borrowing the old definition of the ICT communication networks [2] and applying this to storage of data, we see centralized storage corresponding to a single database, decentralized storage by using data hubs and distributed storage built upon distributed ledger technologies (DLTs). Fig. 1 shows the different possible structures of information storage. The same idea with the three basic structures (centralized, decentralized and distributed) can be applied to the energy system. The chosen data storage structure will be applied to implement all kinds of energy processes, such as market processes or grid operation processes.

Taking the energy market processes as an example, we can construct them according to the centralized, decentralized or distributed data storage structure. The centralized structure would be for example used to support energy wholesale market processes, with a central platform, where all the operations are centralized and the different actors have to send their information to this central platform to perform their business. While, in a decentralized one, there are different data and information storage platforms, which may collaborate for example for supporting regional markets or virtual power plants (VPPs) processes. The last one is the distributed structure, which is built on DLTs and enables the implementation of peer-to-peer transactions without going through any platform. The most well-known DLT is blockchain. Fig. 2 represents those 3 basic energy data storage and management structures, where the red lines interconnecting the components represent information exchange and not power flows.

When considering grid operational processes, there are applications which require a centralized data and information structure. For example, for those bundled energy systems, where the grid operator is at the same time the owner of the energy generation resources and has a centralized platform with all the necessary system data and information. There are

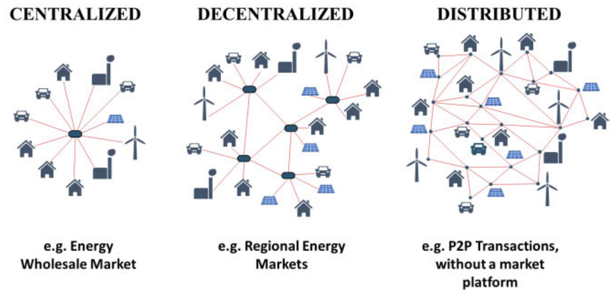

FIGURE 2. Simplified data storage and management structures in the energy system with examples of the supported energy market processes.

also decentralized applications, where for example the energy generating resources are owned by different actors other than the grid operator and therefore, there are different platforms with data and information storage supporting different grid processes. The use of distributed structures for grid operational processes is a more diffuse topic. Some applications relating to distributed control of energy resources or loads may use also distributed data storage and information structures, especially in the field of integration of electromobility or flexibility[1] in power grids, we will discuss those examples in detail in the second section of this paper.

It is clear that the name of distributed generation does not imply that they belong to a distributed data storage and management structure. We find distributed generation in all kind of data storage and management structures and we can find centralized generation (meaning large power stations) also in distributed structures. This clarification may be obvious, but it generates many misunderstandings, mixing up two completely different concepts, which are grid structure and the data management structure.

Many applications in the energy system use as a backbone for information storage and exchange either centralized or decentralized structures. While, applications using distributed structures in the energy system are still rare. Recently, DLT-energy use cases, specially the blockchain based ones, are becoming very popular in energy economics, but to find real implementations outside the research world is still difficult. Those blockchain use cases promise several advantages in front of centralized or decentralized ones, regarding to data sovereignty, disintermediation, automated execution, security, transparency and anonymity as discussed in [4]. However, there are different reasons for the absence of real implementations, among others, the lack of clear business profitability, the lack of experience with DLTs of the energy actors involved in the use case, the regulatory challenges and unclarities, and also the lack of clear standardization processes, tools and results.

In conclusion, applications based on DLTs are nowadays popular in the energy field as they can present clear

[1] The authors did not provide the definition of flexibility in this paper, but we refer to [3] for a full explanation of this topic.

advantages over centralized or decentralized structures. However, in order to have a wide implementation of these applications, there are still some challenges to be overcome. This work focuses on proposing a solution for one of those challenges, which is the need for a standardized reference architecture framework to ensure interoperability. For that, it will first provide an overview of the current DLT-Energy use cases, a classification of those use cases, then justify the necessity for the reference architecture framework specially to facilitate standardization processes. At the end, a solution for this problem will be proposed.

II. DISTRIBUTED STRUCTURES IN THE ENERGY SECTOR

The distributed data storage and management structures considered in this paper are based on Distributed Ledger Technologies (DLT). Due to the complexity of the DLT applications in the energy field, it is not possible to analyze the problematic from a holistic point of view, therefore any analysis must be performed at use cases level. In the following points, DLT-Energy use cases will be presented and a classification for those use cases will be proposed. Since the objective of this work is not to present all possible use cases and analyze them, only a sample of the most popular ones is provided in the following subpoint.

A. DLT-ENERGY USE CASES

There are many DLT-Energy use cases,[2] in this point only the most popular[3] ones are presented as follows.

1) MICROGRID MANAGEMENT

Those use cases are typically dealing with transactive energy management/control for microgrids. This basically means solving complex power system problems while exchanging information about generation, consumption, constraints, and responsive assets over dynamic, real-time forecasting periods, using economic incentive signaling [5], [6]. An example of this use case can be found in [7], where the authors propose a set of interoperable blockchains able to manage energy and financial flows among transacting microgrids. Another example can be found in [8] where the authors propose to integrate blockchain in an Alternating Direction Method of Multipliers (ADMM) algorithm for optimizing energy management of microgrids. An important issue, that is usually taken for granted and therefore remains forgotten in most of those works is how to deal with privacy issues when trading in a closed environment. Reference [9] proposes a solution for this issue focusing on the prosumer privacy and anonymity, by using proven techniques for anonymity, such as mixing services and onion routing.

[2] A quick research provides just in the *IEEE Xplore* a total of 228 results dealing with identification and/or classification of blockchain energy use cases and in the *Web of Science* about 256 results.

[3] The most popular use cases were identified based on the results of an internal survey of the IEC SyC Smart Energy Committee Working Group 8 ''Distributed energy trading infrastructure''.

2) AGGREGATION OF DISTRIBUTED RESOURCES (DR)

There are many examples of using blockchain in the integration of DRs, mostly to enhance some processes in decentralized energy trading platforms for Virtual Power Plants (VPP). Some of the works in this field e.g. [10] are providing a general overview or they are proposing trading algorithms and smart contracts like it can be found in [11] or [12]. Some of them go further by integrating and testing those trading algorithms in a VPPs energy management platform [13], or in ADMM based optimizations [14] or even focusing in the integration with the distribution grid [15].

3) PEER-TO-PEER (P2P) TRADING

This is one of the most popular use cases and there are many different applications of it. The best-known ones are found in the use of P2P to support local energy transactions, to enable energy flexibility markets or to manage bottlenecks. For example, a prosumer, that is, an end consumer with distributed generation capabilities, can sell the additional energy directly to its neighbor, or can react to signals of the grid operator. A review of the works dealing with this use case can be found in [16].

4) INTEGRATION OF ELECTROMOBILITY

In the integration of electromobility use case, there are different applications, for example, in enhancing security protection in data exchange. Reference [17] proposes to use blockchain to monitor dynamic traffic information and idle energy.

5) PROOF-OF-ORIGIN

This use case is one of the few use cases, which have found a relatively wide implementation. An example of application is the generation of cryptocurrencies linked to the production of green energy, such as SolarCoins (SLC) [18]. Other applications are related to market platforms for Guarantees of Origin [19]. Those applications have found an interesting market niche. However, most of these applications are very sensitive to the regulatory framework and, for example, even if the generation of SolarCoins is not prohibited, strictly speaking, it collides with the prohibition of the double sale of green certificates in some countries such as Germany.

B. CLASSIFICATION OF USE CASES

Many efforts have been recently made to identify and classify the DLT-energy use cases. Some of the studies focus on the classification itself, for example [20] develops its classification based on several surveys performed in the field of IoT and Blockchain (see an example of these survey in [21]), or [22] where the focus of the classification is in the underlying business case. An interesting classification is provided by [23], where the authors review a total of 140 research projects and provide a classification on different groups according to the field of activity, implementation platform and consensus strategy use. There are also many papers providing a classification based on marked segments such as [24] or intending only to identify and classify the Energy-DLT use cases based on its contribution in a particular field, such as the contribution to the climate change mitigation presented in [25]. However, the vast majority of the studies are providing a rudimentary classification or just an identification of possible use cases and focusing the work on the analysis or implementation of one of those use cases, such as [26] focusing on a step by step implementation, or [16] and [27] focusing on different trading schemes. Those classifications and use case identifications provide quite similar results and have been analyzed and integrated in a German technical specification (SPEC) VDE SPEC 90008 V1.0 [28] to be published[4] by the German Electrotechnical Commission. This technical specification not only identifies and classifies DLT-energy use cases (see Fig. 3) but also provides guidelines for the industry on how to implement blockchain in regulated and non-regulated use cases.

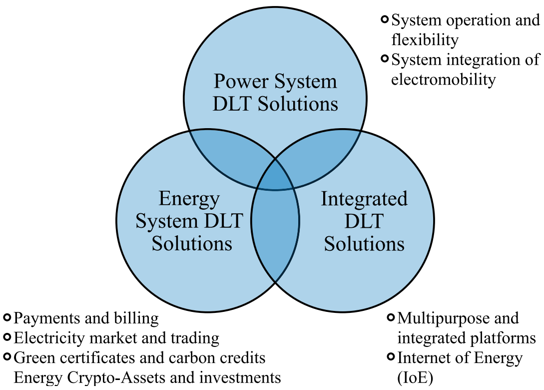

FIGURE 3. Classification and applications of DLT Energy Use Cases according to the German technical specification VDE SPEC 90008 V1.0 [28].

The classification proposed is based on three main use cases categories: Power System DLT Solutions, Energy System DLT Solutions and, Integrated DLT Solutions. The main application fields for the use cases considered in every class are also provided in Fig. 3. The use case category "Power System DLT Solutions" includes those use cases in which the DLT supports solutions in the operation of power supply system. Basically, those use cases which target supporting the system operational processes and the use of flexibilities. Furthermore, this class includes also the integration of electromobility in the power system. The use case category "Energy System DLT Solutions" comprises a total of four areas: The first one includes accounting and billing, which can be automated through DLT, smart contracts and smart metering for consumers and decentralized producers. The second application area is the electricity market and trading through DLT-enabled distributed trading platforms, market operation and management of wholesale markets or commodity trading deals. The third area relates to green certificates and so-called carbon credits. The DLT promises to simplify the fragmented and complex market structures for certificates for renewable energies, emission credits or general environmental attributes. In the fourth area, DLT allows cryptocurrencies to be used as a method to "tokenize" energy assets, creating new markets or business models based on co-ownership and sharing (energy crypto assets and investments). The use case category "Integrated DLT Solutions" includes on the one hand, multipurpose and integrated platforms, e.g. governments, companies or organizations which can set up common platforms to explore the potential of DLT for different cross-cutting use cases. On the other hand, in the context of the Internet of (energy) Things, DLT can enable IoT platforms to communicate between intelligent devices and automation processes, thereby significantly facilitating the interaction between machines and the management of assets. All those use cases in the different classes can be further divided in regulated and non-regulated. This division is extremely important, because it limits drastically the application possibilities.

[4]This technical specification is pending of publication and scheduled to be published in April 2023. The authors of the presented paper are also co-authors of this technical specification.

1) BLOCKCHAIN IN REGULATED USE CASES

The energy economy is a strongly-regulated field. There are limited possibilities to implement and test new technologies, especially those which affects the basic communication structure for the energy processes. Therefore, to implement blockchain in a regulated environment requires lowering the expectations specially regarding to disintermediation, transparency and anonymity. For example, there is the question how to deal with the legal responsibility of the balancing groups, when this role is removed and its functionality is implemented in the blockchain [29].

During 2020 and 2021, there was a working group organized by the German Electrotechnical Commission which tried to find out which DLT-Energy use cases were possible within the German regulatory framework.[5] The results of those meetings are resumed in [28]. Basically, this working group identified the possible use of blockchain only as storage of hashes of monitoring results. Those hashes were used by the grid operators and energy providers for verifying the integrity of the data and not for the exchange of information. This is of course a valid application but it fails to provide a positive cost-benefit analysis, since those actors already have technologies able to do that in place.

2) BLOCKCHAIN IN UNREGULATED USE CASES

Unregulated use cases present a completely different picture. When approaching a possible application of blockchain in the energy sector, the best-known use case would be the P2P transactions between neighbors. One neighbor has a

[5]The name of the group was Working Group 1 of the DKE/AK 901.0.5 "Energy Blockchain". This working group had weekly meetings chaired by Prof. Coll-Mayor in collaboration with many different actors in the German energy economy, such as grid operators, energy providers or components industry.

small PV System, the other one wants for example, to charge its electrical vehicle and both need an infrastructure that allows doing that. Those are use cases where a centralized or decentralized information storage structure would not make much sense. Therefore, it is a possible application for distributed structures. There are also interesting applications while generating tokens for different purposes, for example as pay-back points or as proof of origin of green energy. Even though, those use cases can be considered at least partially as unregulated from the point of view of the energy system, they are also affected but the ambiguities in the general regulatory framework. Examples of that are found in the use of crypto-assets, legally bounding smart contracts, or Data Protection Regulation. Regarding to the general regulatory situation in the field of crypto-assets in Europe, there is a very interesting publication of the European Blockchain Observatory and Forum [30], it analyses the implementation of decentralized finance (DeFi) and crypto-assets in the European countries.

In conclusion, in this point, the most well-known DLT-Energy applications and use cases have been presented, a classification based in the German technical specification VDE SPEC 90008 V1.0 has been proposed and the importance of dividing the use cases in regulated and non-regulated has been emphasized. In the next sections, the importance of reference architectures and frameworks for DLT-Energy use cases will be justified.

III. THE NEED OF REFERENCE ARCHITECTURES & FRAMEWORKS IN THE USE CASE ANALYSIS

Each use case (UC) can be executed in different solution architectures depending on the chosen approach. Therefore, examining a concrete implementation offers only limited value when analyzing use cases. However, capturing the essence of all possible implementations offers a more complete view. This essence is called the reference architecture and it is essentially done by collecting a set of patterns observed across a number of successful implementations and best practices. A reference architecture (RA) can be viewed as a model solution for an architecture for a use case or a group of use cases. These RAs are often used to provide a common language for the various stakeholders, to provide consistency of implementation of technology across different use cases, to provide benchmarking basis, to encourage adherence to common standards, specifications, and patterns [31]. The topic of RAs has been broadly researched specially in the field of software engineering, in which RAs are used for different purposes, e.g., standardization to ensure interoperability, or facilitation of software design by providing guidelines for system design [32].

When analyzing many different UCs, we can end-up with different RAs. To be able to assess the interactions and boundaries, we need tools which help us to adequately describe and collect requirements, without mandating any specific architecture type, this is called RA framework. Frameworks cover conventions, principles and practices for the description of architectures established within a specific domain of application and/or community of stakeholders [33]. Furthermore, frameworks help architects structure their thinking by dividing the architecture description into domains, layers or views [34]. Even if the difference between RA and RA framework is clear, in many references it can get blurry or even be indistinctly used.

A. USE OF RA & RA FRAMEWORKS IN THE ENERGY SECTOR

Even though the use of RA and RA frameworks is established and well known in software engineering, its use in system-oriented engineering is more recent. First attempts to define the concept of RAs can be found in 2010 [35]. However, the interest for RAs in the energy field is even more recent, with first serious intents dating from 2011 [36] and 2012 [37]. The trigger for this interest was mainly the increase in the complexity in the processes and architectures of the energy system. We can find reasons for this increased complexity, e.g. in the change of responsibilities of the energy system stakeholders partially due to unbundling, to the increase in the penetration of distributed resources, to the appearance of smart loads or to the inclusion of advanced metering infrastructures. Furthermore, a RA is very helpful in comprehending the use case at an abstract level, which helps in tasks such as the design of incentive-based subsidies or regulatory frameworks, the development of standards, legislation, discussions on a national or international level, market design or the collaboration between different domains [38]. Currently, we find RAs for many different applications in the energy system, from flexibility activation [39], to grid-customer interaction [40], or cloud-based flexibility services [41], or decentralized control architectures [42], or electrical vehicle charging [43], or self-healing distribution networks [44], or for aggregators [45], or for implementing large-scale smart grids [46], or many others. We can extrapolate some conclusions analyzing those works. First, most of those reference architectures have in common that they are created based on functional requirements, but for [43] which also includes business requirements. Second, most of the works use different frameworks, which makes it very difficult to compare those RAs and find any similarities or common ground, except for [41] and [46] which are more or less using the Smart Grids Architecture Model (SGAM[6]) as framework. Third, in some papers there is confusion about what RA means, e.g. in [46] the authors are defining a framework and not an architecture and therefore the title of the work seems to be misleading. Papers [42] and [44] are dealing with the test architecture and system topology respectively, therefore, the name 'reference architecture' seems to be misplaced.

B. USE OF RA & RA FRAMEWORKS IN THE DLT SECTOR

The RAs are quite common in the ICT sector, therefore there are many works dealing with DLT and Blockchain RAs.

[6]The SGAM is a standardized reference architecture framework for smart grids applications and due to its importance for this work, it will be explained in detail in the following points.

However, most of these works refer to standardized RAs, see the next section, or are RAs based on use cases from sectors other than energy, such as supply chains or health. A further analysis of those solutions has not been considered in this work.

C. USE OF RA & RA FRAMEWORKS IN THE ENERGY-DLT SECTOR

Finally, in the use of RA for DLTs in the energy sector, there are different intents to propose a RA but mostly remain at a conceptual model level. Those conceptual models provide a high-level vision of the inclusion of the DLT in different energy use cases focusing on different aspects. For example [47] presents a conceptual model that highlights the application of blockchain technology to the smart grid to help reduce costs by cutting out 3rd parties and increasing the arbitrage opportunity for individuals to produce and sell energy to each other. This reference goes further by exploring how in this case the use of blockchain can improve smart grid cyber resiliency. Another interesting work can be found in [48], the authors here highlight and discuss different concepts and technologies to enable Peer-to-Peer transactive energy exchanges and Local Energy Markets. However, the most interesting output of this work is that it is a first attempt to propose a reference framework for inclusion of Blockchain in transactive management infrastructures, creating three different layers for the organizing the different processes, including energy and Blockchain processes.

As a conclusion, it can be derived, that the use of RAs helps to analyze the use case from an abstract point of view. Nowadays, they are quite often applied to provide a generalized approach to a UC or group of UCs. However, a RA framework is necessary to compare the different RAs and to find common blocks and similarities. Moreover, even being this importance clear, the work in RA frameworks in the DLT-Energy sector (outside the standardization arena) is still limited.

IV. THE STANDARDIZATION ARENA FOR DLT-ENERGY REFERENCE ARCHITECTURES & FRAMEWORKS

Standardization is one of the challenges which are undermining the implementation of DLT-Energy use cases, as stated in the introduction. One of the main problems is not just the lack of standardization but the fragmentation of the standardization activities. There is a need for collaboration and cohesion and even development of common tools to enable the discussion across areas such as Identity, cross-chain and off-chain Interoperability, Governance and Smart Contracts [49] and in their integration in critical sectors,[7] such as energy. The global standardization community is actively working to develop standards related to DLT and blockchain and most of the international standardization bodies have focused groups on DLT/Blockchain from different perspectives, see a scan of current standardization activities in [50]. However, there are only a few activities focusing on solving the problematic of the integration of DLT/Blockchain in Energy use cases.

Within this section, a state of the art of the situation in DLT-Energy standardized common reference architectures and frameworks will be provided, with the objective to be used to map and to analyze DLT-Energy use cases with focus on interoperability.

A. CURRENT STANDARDIZATION ACTIVITIES IN RAS AND RA FRAMEWORKS USEFUL FOR MAPPING DLT – ENERGY USE CASES

The efforts of the main standardization bodies in the field of Blockchain/DLT RA & RA Frameworks will be presented in this point. Since some of the documents are at the moment still under development and are not found in the public domain, only the available draft versions will be analyzed and referred. An overview of these activities can be found in Table 1.

1) ISO/TC 307 "BLOCKCHAIN AND DLTs"

The ISO/TC 307 ''Blockchain and distributed ledger technologies'' has recently published a new standard called ISO 23257 ''Blockchain and distributed ledger technologies — Reference architecture'' [52]. This standard specifies a RA for DLTs, which addresses concepts, cross-cutting aspects, architectural considerations, and architecture views, including functional components, roles, activities, and their relationships. The proposed RA uses a view-point approach, including in its analysis the user, functional and systemic view. Interesting is the attempt to describe the DLT ecosystem, including roles and activities and necessary functions to support the different use cases. Even though, the focus is only on the DLT part of the system, it does consider interactions with non-DLT systems and even other DLT systems. As a conclusion, this standard provides a good system view of the functional components needed in use cases dealing with DLTs, but does not attempt to identify or analyze applications. With focus on DLT-Energy use cases, this standard is useful for identifying necessary components, functions and interactions, but does provide a framework where those use cases can be mapped.

2) ITU-T FOCUS GROUP ON APPLICATION OF DLT

The ITU-T Focus Group on Application of Distributed Ledger Technology (FG DLT) has also published a Technical Specification called ''Distributed ledger technology reference architecture'' [53]. This document specifies a RA for DLTs, including the hierarchical relationship, specific functions and core components of the architecture. It provides a similar RA as the ISO 23257, but focusing more on functionalities instead of functional components. Furthermore, the ISO standard provides a useful description of the DLT ecosystem which is missing in this technical specification. Regarding to the interaction with non-DLT Systems,

[7] In the European Digital Strategy [51], the critical sectors identified are energy, climate change and environment, manufacturing, agriculture and health.

TABLE 1. Summary of current standardization activities in RAs & RA frameworks in DLT or DLT-Energy.

	Standardization body	Current outputs	State of the art and focus
Development of a RA	ISO/TC 307 "Blockchain and DLTs"	ISO 23257 "Blockchain and distributed ledger technologies — Reference architecture" has been published	Published. This RA uses a view-point approach, including in its analysis the user, functional and systemic view, but does not attempt to identify or analyze applications. Furthermore, it does not provide a framework where the involved use cases can be mapped.
	ITU-T Focus Group on Application of DLT	Technical Specification "Distributed ledger technology reference architecture"	Published. It contains a similar RA as the ISO 23257, but focusing more on functionalities instead of functional components.
	ETSI Industry Specification Group (ISG) Permissioned Distributed Ledger (PDL)	PDL-012 – "Reference Architecture Framework Specifically based on the scenarios analyzed by PDL-003"	Published. This RA is only applicable for PDLs (permissioned distributed ledgers).
	CEN CENELEC JTC19 "Blockchain and DLTs"	Technical Specification called "Decentralised Identity Management Model based on Blockchain and other Distributed Ledgers Technologies. – Part 1: Generic Reference Framework"	In drafting. RA for DIM, aligned to the EU regulatory frameworks that support the Digital Single Market, including the proposed eIDAS Regulation, the Single Digital Gateway Regulation and the General Data Protection Regulation.
Development of a RA	IEEE Blockchain initiative Energy Working Group	P2418.5 - Standard for Blockchain in Energy	In drafting. It proposes a cybersecurity stack that can be also understood as an architectural framework.
	IEC SyC SE WG 8 "Distributed energy trading inf."	Two PWI (Preliminary work Items): PWI1: Extension of the SGAM to include Distributed Ledger Technologies PWI2: Archetypes of DLT-based business models for the energy sector	In drafting. The work is still in a very preliminary stage.

this technical specification is more concrete in identifying exactly in which layer and which functionalities will enable that, while the ISO just identifies the components involved. Similar as the ISO 23257, this specification is useful for identifying necessary functionalities and interactions, but does not attempt to provide a RA framework where DLT-Energy use cases can be mapped.

3) CEN CENELEC JTC19 "BLOCKCHAIN AND DLTs"

CEN CENELEC JTC19 "Blockchain and Distributed Ledger Technologies" is giving priority to Decentralised Identity Management (DIM) in relation to the proposed revision of the eIDAS Regulation [54]. The CEN CENELEC JTC19 has a Working Group (WG 1) which is preparing a Technical Specification called "Decentralised Identity Management Model based on Blockchain and other Distributed Ledgers Technologies. – Part 1: Generic Reference Framework". The objective of this document is to develop a RA for DIM, aligned to the EU regulatory frameworks that support the Digital Single Market, including the proposed eIDAS Regulation, the Single Digital Gateway Regulation and the General Data Protection Regulation. The document is still under drafting, and the focus is to ensure that DIM will follow the European regulation. Therefore, it is not expected that this document provides any framework where DLT-Energy use cases can be mapped.

4) ETSI INDUSTRY SPECIFICATION GROUP (ISG) PDL

The ETSI Industry Specification Group (ISG) PDL aims to provide the foundations for the operation of permissioned distributed ledgers (PDL) and has published several deliverables regarding to application scenarios or smart contracts between others. One of the deliverables is focusing on the problem of the RA, it is called PDL-012 – "Reference Architecture Framework Specifically based on the scenarios analyzed by PDL-003" [55] being PDL-003 the application scenarios defined by this group. This document focuses in the definition of a RA only applicable for PDLs. In comparison with the other presented RAs, this one focusses on services which can be provided by PDLs. The structure may be similar to the ITU-T one, but it is not applicable to all DLTs and the interactions between the services inside and outside layers are not identified.

5) IEEE BLOCKCHAIN INITIATIVE ENERGY WORKING GROUP

The IEEE Blockchain initiative covers data, interoperability, governance, identity and smart contracts in the following thematic areas: Energy, IoT, Healthcare, FinTech, Cryptocurrency and Digital Asset. The Blockchain for Energy Working Group is developing the future standard P2418.5 - Standard for Blockchain in Energy [56], and it should include the development of a RA framework. So far, the authors of this paper do not have information of available drafts, but the following publication, see [57], presents the work done aimed to establish the cybersecurity foundations for the IEEE P2418.5 Standard for Blockchain in this working group. The proposed cybersecurity stack can be also understood as an architectural framework. Even though this work represents the most advance intent to couple the SGAM framework with an ICT framework able to map DLT-Energy use cases, the results presented are still in an early stage and the proposed examples for mapping use cases do not show clearly the interaction between energy and DLT.

6) IEC SyC SE WG 8 "DISTRIBUTED ENERGY TRADING INF."

The IEC SyC Smart Energy Working Group 8 called "Distributed energy trading infrastructure" is a newly funded working group under the IEC Smart Energy Committee. Its focus is to develop and propose new standards under the subject of distributed energy trading infrastructures. The first projects of this group are to provide an extension of the SGAM to include DLTs and to define the necessary ecosystem for implementing DLT-based business models in the energy sector. The ideas presented in this paper build up the basis for the work of this new working group.

7) THE SMART GRIDS ARCHITECTURE MODEL (SGAM)

The SGAM is a standardized reference architecture framework broadly used for mapping energy use cases with standardization purposes. The SGAM is extremely helpful for analyzing energy use cases from different perspectives, from business goals to basic layout of components. Once those components are mapped, then the communication infrastructure can be drawn and the different communication and information protocols can be identified.

The structure of the SGAM [58] is built upon the NIST Conceptual Model [59], the GridWise Architecture Council's eight-layer stack [60] and the conventional automation pyramid, with influences from many different working teams and experts.[8] The SGAM has three dimensions. The first dimension addresses the traditional domains in the energy economy (generation, transmission, distribution, DER and customer premises). The second dimension consists of five layers representing business objectives and processes, functions, information exchange and models, communication protocols and components. The third dimension refers to the information management zones (market, enterprise, operation, station, field and processes). In general, the SGAM is a broadly used RA model or framework to map use cases in the energy system, but it is not adequate to map DLT-Energy use cases, as it will be explained in the next section.

B. COMPARING THE CURRENT STANDARDIZATION ACTIVITIES IN RAs & RA FRAMEWORKS IN DLT OR DLT-ENERGY

Firstly, it must be emphasized that some of the presented work in standardization bodies are RAs and some of them are RA frameworks: The ISO 23257, the ITU-T technical specification and the ETSI PDL-012 are RAs. However, the CEN/CENELEC technical specification, the SGAM and the IEEE P2418.5 propose a RA framework. Secondly, because many of the different RAs presented in the different standardization bodies are based on different RA frameworks, even if some of them are loosely inspired in the Open Systems Interconnection (OSI) model [61], they cannot be easily compared and therefore they must be addressed separately. This can make comparisons difficult. Thirdly, the definition of DLT-Energy RA frameworks is still in a very early stage. From the RA frameworks proposed in the standardization bodies, the one from CEN/CENELEC is not available yet and so far, and it is not even targeting DLT-Energy use cases. The one proposed by IEEE is in an early state, therefore it is difficult to extrapolate any conclusions. The SGAM is useful to map energy use cases but it is not thought for mapping DLT use cases. Fourthly, most of the standardization bodies addressing standardization of Blockchain/DLT are looking at the problematic from the point of view of the ICT sector. There are few works on the interaction between ICT and Energy and this generates problems in the communication between bodies and in the correct interpretation of proposed solutions.

In conclusion, this section has presented the main activities and standardization efforts in the field of RAs and RA frameworks dealing with DLT and DLT-Energy use cases. There are different interpretations and RAs, which make it very difficult to exchange information between standardization activities. A common RA framework would solve this problem and provide a suitable collaboration platform for analyzing use cases. Unfortunately, so far, no suitable RA framework has been identified to support DLT-Energy use case mapping to assess, for example, interoperability issues.

V. DEFINING A COMMON REFERENCE FRAMEWORK TO ASSES DLT-ENERGY USE CASES

As stated in the section above, the mapping of use cases is a very useful method to assess for example interoperability problems. To map different use cases in a coherent way, it is important to use a common RA Framework. In the energy field, one of the most well-known RA frameworks is the SGAM. Unfortunately, the SGAM presents several limitations when trying to map use cases including DLT functionalities.

A. REQUIREMENTS FOR A COMMON DLT-ENERGY REFERENCE ARCHITECTURE FRAMEWORK

In the opinion of Mr. C. Lima[9] "A generic reference framework should focus on establishing the interfaces and interconnections between different actors and helping establish the methodologies to define the classification and subclassification of several parts of complex systems, including the definition of the terminology and classification of each subsystem" [62]. Basically, this defines the general requirements

[8]The Smart Grid Reference Architecture was developed by the CEN-CENELEC-ETSI Smart Grid Coordination Group in Nov. 2012.

[9]Claudio Lima is Chairperson of the IEEE Blockchain/DLT in Energy P2418.5 Standards WG which includes Standardization in "Architecture and Reference Frameworks" for DLT-Energy use cases.

needed for a new reference architecture (RA) framework. In the case of a DLT-Energy RA framework, following concrete requirements are deemed as necessary. It must:

- Provide a clear definition of the ecosystem, identifying and defining the user roles.
- Define the archetypes as a set of basic characteristics that a user role has to fulfill, when performing any task in the DLT.
- Identify the domains in which the architecture will be defined, in some references these domains are also called *architectural viewpoints* [63].
- Describe the methodology and the processes which will support the mapping of the use cases in the RA framework.
- Ensure coherence with current successful reference architecture models, such as the SGAM.
- Ensure capability to adapt the current standardized reference architectures into the framework.

B. LIMITATIONS OF THE SGAM IN MAPPING DLT USE CASES

The SGAM is adequate for energy use cases, but has also several limitations. When mapping centralized and decentralized storage of information structures, all of the functionalities needed to support a concrete business case are implemented as functionalities in different components. In the case of a decentralized structure, those functionalities are shared between many different components and in the case of a centralized structure, the functionalities are usually relaying in one or few components. That implies that we can easily find a correspondence between components and functionalities. In the SGAM the functions layer is above the components layer and mapping functionalities in one layer with corresponding components in another layer below it, it is relatively easy. In distributed structures, this is not the case as the functionalities are not always implemented in the components, but partially in the distributed layer, depending on if we are proposing off-chain or on-chain decision algorithms.

C. UPGRADING THE SGAM FOR MAPPING DLT-ENERGY USE CASES

Taking into account, that the focus is to develop a useful RA framework which can be broadly accepted, the logical step is to use an existing framework and updating it for including DLT-Energy use cases. The chosen framework will be the SGAM. The usability of the SGAM to assess interoperability in energy use cases is already proven and the SGAM is a mature framework, which is already accepted for the majority of stakeholders of the energy field. This upgrade of the SGAM has been proposed in the [28] and will support the standardization efforts of the International Electrotechnical Commission (IEC).[10]

[10]This proposed reference architecture will be part of a new technical report under the domain of the IEC SyC Smart Energy Working Group 8.

1) DEFINING THE NEW ECOSYSTEM: ROLES AND ARCHETYPES

The roles in DLT-Energy use cases are basically the roles that the stakeholders in the energy system assume, meaning for example grid operator, end customer, energy provider, etc.

TABLE 2. Definition of DLT archetypes based on [28].

Archetype	Tasks	Examples of roles
Initiator	▪ Establishment of an industrial consortium ▪ Development of business governance rules ▪ Development of market processes ▪ Define incentives for all the stakeholders ▪ Define technology-stack	▪ In the case of regulated UCs, this role is taken by for example regulatory authorities. ▪ In the case of unregulated UCs, the assignment is open, i.e. in principle any stakeholder can take these tasks, e.g. agencies or associations
Supplier / Comple-mentor	▪ Offering and delivering products and services ▪ Defining and programming the smart contracts	▪ An energy service provider who offers one or more services (e.g. energy supply for electromobility) via DLT.
Consumer / User	▪ Finding out and getting information about offers ▪ Buying products and services	▪ EV driver, which wants to buy energy. ▪ Network operator (NO), which acquires flexibility as a service. ▪ Prosumers/producers, which want to sell surplus electricity.
Curator	▪ Development & maintenance of the platform ▪ Operating the platform ▪ Quality monitoring	▪ This may need a new role in the energy system, the name could be "DLT service provider". This role takes on the responsibility for the entire IT infrastructure.
Modulator	▪ Offering services to facilitate transactions.	▪ The role which takes on this task will strengthen the DLT platform by joining forces with other players to ensure its smooth operation and promote synergy effects. This could be for example a provider of charging stations.
Ecosystem Comple-mentor	▪ Offering related products and services to adjacent markets.	▪ This should be a role which is active in one use case and at the same time offers services in another unrelated use case.

The archetypes define the characteristics that the roles required to act in the DLT. Those archetypes can be assigned to the different exiting roles or can require new roles. So far, six architypes have been identified, see names and tasks of those archetypes in Table 2; another column has been added to provide some examples of the roles in the energy system and corresponding archetypes.

2) METHODOLOGY

The idea is to expand the SGAM in such a way that the DLT-based energy use cases can be properly mapped. The decision was to keep the basic SGAM structure with its domains,

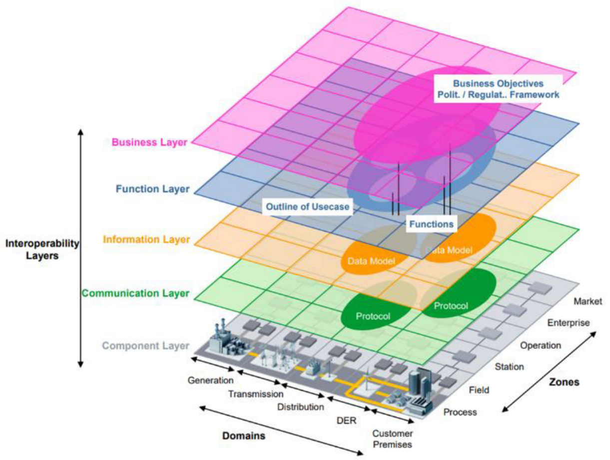

FIGURE 4. The Smart Grids Architecture Model (SGAM) taken from [58], with its interoperability layers, domains and zones.

layers and zones, and just include for the part of the use case which will take place in the DLT as a parallel structure. This makes easier for the system architect to clearly identify which part of the process is placed in the DLT, which part of the process is not. From the business point of view, the business use case is mapped in the SGAM Business layer, from the components point of view, the system is mapped in the SGAM component layer and from the functional, information and communication point of view, the system has interactions with the DLT. This is a pragmatic decision, which enables the mapping of use cases as until now, which was important. For the business and components point of view, it remains business as always, for the other SGAM layers, only the interactions with the DLT must be considered.

3) NEW DLT LAYERS

Even though, the SGAM will be used as the basis for the RA framework, the DLT will need also a structure. It is in the best interest of our community to try to find common ways to avoid fragmentation in standardization, therefore, the idea proposed in [54], which is stated to be the basis for the future proposed IEEE P2418.5 DLT cybersecurity stack, has been basically used, but adapted to the new needs and with an effort to find a coherence with the work of the ISO/TC 307. The result can be found in Table 3, illustrating the different layers and providing their short descriptions.

4) EXTENSION OF THE SGAM WITH THE NEW DLT LAYERS

The interaction between the SGAM Layers and the new DLT layers are found in Fig. 5. When describing the reference architecture of a use case or group of use cases, the interactions between the SGAM and the DLT layers, will be specified. In the RA framework, it is only necessary to provide, where these interactions exist, but not to pre-define how these interactions will take place.

TABLE 3. New DLT layers based on [28].

Layer name	Description
Service layer	This layer contains applications, software, scripts, and programs that can be used by users or other applications to interact with DLT. Some of these applications can also be located outside of the DLT system and connected via DLT Oracle. As such, there is a strong overlap with the SGAM functional layer where the off-chain functions take place.
Application layer	This layer contains the program logic within the DLT such as smart contracts or the chain code. The code and rules from the application layer are applied by the service layer, which in turn directs the code to perform a transaction. The latter takes place in the transaction data layer.
Transactions Data layer	This layer is activated by the application layer to perform transactions.
Consensus layer	This layer is a critical security component of DLT. It creates trust in the correctness of transactions in terms of integrity, authenticity and accountability. The consensus also forms the basis for further process steps within the distributed system, such as the formation of acceptance and the release of blocks or processing and distribution fees.
Trusted Network layer	The trusted network layer maps the communication infrastructure through which the transactions and the exchange of information and data between the nodes takes place. Protocols and methods to facilitate discovery and communication between participants reside in this layer.
Data devices layer	In this layer are the virtual and physical computers or software agents that act as authorized participants. Herein, the nodes must be able to perform cryptographic operations (e.g. digital signatures and hashing), obtain and also change the identity of other nodes, and provide their identity information for authentication and authorization by the network/other nodes. There is a strong overlap between this layer and the communication and information layers of SGAM.

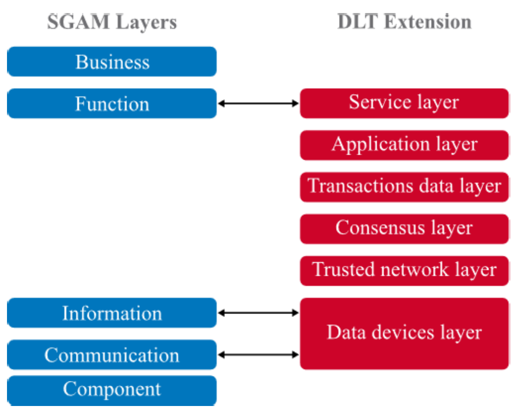

FIGURE 5. Interactions between SGAM layers and new DLT layers.

In conclusion, this section has proposed several concepts to develop a new standardized RA Framework to map and analyze DLT-Energy use cases, with focus on interoperability. These ideas will be discussed and implemented in a new IEC technical specification.

VI. CONCLUSION

In this paper, we have identified the most popular DLT-Energy use cases and presented a classification of those use cases. Furthermore, we discussed the need of a common architecture reference framework to map those use cases with focus on interoperability issues. Since interoperability has to be treated from the standardization point of view, the current situation in the main international standardization bodies in this field has been analyzed. In the end, a solution for a new architecture reference framework has been proposed. This new architecture reference framework will be proposed for standardization and discussed within the new IEC SyC Smart Energy Working Group 8 "Distributed energy trading infrastructure".

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REFERENCES

[1] G. Fulli et al., "Blockchain solutions for the energy transition, experimental evidence and policy recommendations," Publications Office Eur. Union, Luxembourg, Europe, Tech. Rep. EN EUR 31008, 2022.

[2] P. Baran, "On distributed communications networks," *IEEE Trans. Commun. Syst.*, vol. CS-12, no. 1, pp. 1–9, Mar. 1964.

[3] C. Eid, P. Codani, Y. Perez, J. Reneses, and R. Hakvoort, "Managing electric flexibility from distributed energy resources: A review of incentives for market design," *Renew. Sustain. Energy Rev.*, vol. 64, pp. 237–247, Oct. 2016.

[4] *Blockchain in the Energy Sector: The Potential for Energy Providers*, German Federal Assoc. Energy Water Manag. (BDEW), Berlin, Germany, May 2018. [Online]. Available: https://www.bdew.de/media/documents/Studie-Blockchain-englische-Fassung-Dez.2018.pdf

[5] J. Hu, G. Yang, K. Kok, Y. Xue, and H. W. Bindner, "Transactive control: A framework for operating power systems characterized by high penetration of distributed energy resources," *J. Modern Power Syst. Clean Energy*, vol. 5, no. 3, pp. 451–464, May 2017.

[6] D. Coll-Mayor and A. Notholt, "Development and test of distributed ledger technologies applications in a microgrid distributed control," in *Proc. Int. Conf. Renew. Energies Power Quality (ICREPQ)*, Tenerife, Spain, Apr. 2019, pp. 1–5.

[7] Z. Li, S. Bahramirad, A. Paaso, M. Yan, and M. Shahidehpour, "Blockchain for decentralized transactive energy management system in networked microgrids," *Electr. J.*, vol. 32, no. 4, pp. 58–72, May 2019.

[8] E. Münsing, J. Mather, and S. Moura, "Blockchains for decentralized optimization of energy resources in microgrid networks," in *Proc. IEEE Conf. Control Technol. Appl. (CCTA)*, Aug. 2017, pp. 2164–2171. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/8062773

[9] A. Laszka, A. Dubey, M. Walker, and D. Schmidt, "Providing privacy, safety, and security in IoT-based transactive energy systems using distributed ledgers," in *Proc. 7th Int. Conf. Internet Things*, Oct. 2017, pp. 1–8.

[10] S. Cantillo-Luna, R. Moreno-Chuquen, H. R. Chamorro, V. K. Sood, S. Badsha, and C. Konstantinou, "Blockchain for distributed energy resources management and integration," *IEEE Access*, vol. 10, pp. 68598–68617, 2022.

[11] J. Lu, S. Wu, H. Cheng, and Z. Xiang, "Smart contract for distributed energy trading in virtual power plants based on blockchain," *Comput. Intell.*, vol. 37, no. 3, pp. 1445–1455, Aug. 2021.

[12] T. Cioara, M. Antal, V. T. Mihailescu, C. D. Antal, I. M. Anghel, and D. Mitrea, "Blockchain-based decentralized virtual power plants of small prosumers," *IEEE Access*, vol. 9, pp. 29490–29504, 2021.

[13] Q. Yang, H. Wang, T. Wang, S. Zhang, X. Wu, and H. Wang, "Blockchain-based decentralized energy management platform for residential distributed energy resources in a virtual power plant," *Appl. Energy*, vol. 294, Jul. 2021, Art. no. 117026.

[14] Q. Yang and H. Wang, "Exploring blockchain for the coordination of distributed energy resources," in *Proc. 55th Annu. Conf. Inf. Sci. Syst. (CISS)*, Mar. 2021, pp. 1–6.

[15] W. Shao, W. Xu, Z. Xu, B. Liu, and H. Zou, "A grid connection mechanism of large-scale distributed energy resources based on blockchain," in *Proc. Chin. Control Conf. (CCC)*, Jul. 2019, pp. 7500–7505.

[16] E. A. Soto, L. B. Bosman, E. Wollega, and W. D. Leon-Salas, "Peer-to-peer energy trading: A review of the literature," *Appl. Energy*, vol. 283, Feb. 2021, Art. no. 116268.

[17] H. Liu, Y. Zhang, and T. Yang, "Blockchain-enabled security in electric vehicles cloud and edge computing," *IEEE Netw.*, vol. 32, no. 3, pp. 78–83, May 2018.

[18] L. Johnson, A. Isam, N. Gogerty, J. Zitoli. (Dec. 2015). *Connecting the Blockchain to the Sun to Save the Planet*. [Online]. Available: https://ssrn.com/abstract=2702639

[19] J. A. F. Castellanos, D. Coll-Mayor, and J. A. Notholt, "Cryptocurrency as guarantees of origin: Simulating a green certificate market with the Ethereum Blockchain," in *Proc. IEEE Int. Conf. Smart Energy Grid Eng. (SEGE)*, Aug. 2017, pp. 367–372.

[20] T. Alladi, V. Chamola, J. J. P. C. Rodrigues, and S. A. Kozlov, "Blockchain in smart grids: A review on different use cases," *Sensors*, vol. 19, no. 22, p. 4862, Nov. 2019.

[21] H.-N. Dai, Z. Zheng, and Y. Zhang, "Blockchain for Internet of Things: A survey," *IEEE Internet Things J.*, vol. 6, no. 5, pp. 8076–8094, Oct. 2019.

[22] M. J. Bürer, M. de Lapparent, V. Pallotta, M. Capezzali, and M. Carpita, "Use cases for blockchain in the energy industry opportunities of emerging business models and related risks," *Comput. Ind. Eng.*, vol. 137, Nov. 2019, Art. no. 106002.

[23] M. Andoni et al., "Blockchain technology in the energy sector: A systematic review of challenges and opportunities," *Renew. Sustain. Energy Rev.*, vol. 100, pp. 143–174, Feb. 2019.

[24] M. Hinterstocker, C. Dufter, S. von Roon, A. Bogensperger, and A. Zeiselmair, "Potential impact of blockchain solutions on energy markets," in *Proc. 15th Int. Conf. Eur. Energy Market (EEM)*, Jun. 2018, pp. 1–5.

[25] G. Dorfleitner, F. Muck, and I. Scheckenbach, "Blockchain applications for climate protection: A global empirical investigation," *Renew. Sustain. Energy Rev.*, vol. 149, Oct. 2021, Art. no. 111378.

[26] F. Knirsch, A. Unterweger, and D. Engel, "Implementing a blockchain from scratch: Why, how, and what we learned," *EURASIP J. Inf. Secur.*, vol. 2019, no. 1, pp. 1–10, Dec. 2019.

[27] W. Tushar et al., "Grid influenced peer-to-peer energy trading," *IEEE Trans. Smart Grid*, vol. 11, no. 2, pp. 1407–1418, Mar. 2020.

[28] *Distributed Ledger Technologien in der Energiewirtschaft*, Tech. Specification VDE SPEC 90008 V1.0, German Assoc. Elect., Electron. Inf. Technol. (VDE), Frankfurt, German, Dec. 2022.

[29] *Die Blockchain-Technologie Potenziale und Herausforderungen in den Netzsektoren Energie und Telekommunikation*, German Federal Netw. Agency Electr., Gas, Telecommun., Post Railways (Bundesnetzagentur), Bonn, German, Nov. 2019. [Online]. Available: https://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Allgemeines/Bundesnetzagentur/Publikationen/Berichte/2019/DiskussionspapierBlockchain.pdf;jsessionid=3DA9A4BD3B2A8862E547F6E91A408DEE?__blob=publicationFile&v=2

[30] *EU Blockchain Ecosystem Developments*, EU Blockchain Observatory and Forum, Brussels, Belgium, Aug. 2022. [Online]. Available: https://www.eublockchainforum.eu/sites/default/files/reports/eu_ecosystem_report_20220909_final%20version_1.pdf

[31] Office of the Assistant U.S. Secretary of Defense. (Jun. 2010). *Networks and Information Integration (OASD/NII): Reference Architecture Description*. U.S. Department of Defense. [Online]. Available: https://www.acqnotes.com/Attachments/Reference%20Architecture%20Description,%20June%202010.pdf

[32] S. Angelov, P. Grefen, and D. Greefhorst, "A classification of software reference architectures: Analyzing their success and effectiveness," in *Proc. Joint Work. IEEE/IFIP Conf. Softw. Archit. Eur. Conf. Softw. Archit.*, Sep. 2009, pp. 141–150.

[33] *Systems and Software Engineering—Architecture Description*, document SO/IEC/IEEE 42010:2011(en), 2011.

[34] M. Galster, "Software reference architectures: Related architectural concepts and challenges," in *Proc. 1st Int. Workshop Exploring Component-based Techn. Constructing Reference Architectures (CobRA)*, May 2015, pp. 1–4.

[35] R. Cloutier, G. Müller, D. Verma, R. Nilchiani, E. Hole, and M. Bone, "The concept of reference architectures," *Syst. Eng.*, vol. 13, no. 1, pp. 14–27, 2010.

[36] *IEEE Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation With the Electric Power System (EPS), End-Use Applications, and Loads*, Inst. Elect. Electron. Eng., Piscataway, NJ, USA, Sep. 2011.

[37] *The M/490 Mandate Smart Grids Reference Architecture*, Eur. Standards Organizations (ESO), Turkey, Nov. 2012.

[38] M. Irlbeck, D. Bytschkow, G. Hackenberg, and V. Koutsoumpas, "Towards a bottom-up development of reference architectures for smart energy systems," in *Proc. 2nd Int. Workshop Softw. Eng. Challenges Smart Grid (SE4SG)*, May 2013, pp. 9–16.

[39] H. Keko, P. Hasse, E. Gabandon, S. Sučić, K. Isakovic, and J. Cipriano, "Secure standards-based reference architecture for flexibility activation and democratisation," *CIRED Open Access Proc. J.*, vol. 2020, no. 1, pp. 584–587, Jan. 2020.

[40] G. Accetta, D. D. Giustina, S. Zanini, G. D'Antona, and R. Faranda, "SmartDomoGrid: Reference architecture and use case analyses for a grid-customer interaction," in *Proc. IEEE PES ISGT Eur.*, Oct. 2013, pp. 1–4.

[41] B. A. Bremdal et al., "Towards a reference architecture for cloud-based flexibility services in the electricity domain," in *Proc. CIRED Berlin Workshop (CIRED)*, Sep. 2020, pp. 783–786.

[42] B. Petersen, T. Brasch, H. Bindner, B. Poulsen, and S. You, "Controlling entity ICT reference architecture: Distributed control architecture for distributed systems," in *Proc. IEEE 12th Int. Conf. Compat., Power Electron. Power Eng. (CPE-POWERENG)*, Apr. 2018, pp. 1–6.

[43] F. Lehfuß, M. Nöhrer, E. Werkman, J. A. Lópezz, and E. Zabalaz, "Reference architecture for interoperability testing of electric vehicle charging," in *Proc. Int. Symp. Smart Electric Distribution Syst. Technol. (EDST)*, Sep. 2015, pp. 341–346.

[44] T. Berry and Y. Chollot, "Reference architecture for self healing distribution networks," in *Proc. IET Int. Conf. Resilience Transmiss. Distribution Netw. (RTDN)*, Sep. 2015, pp. 1–5.

[45] D. E. M. Bondy, K. Heussen, O. Gehrke, and A. Thavlov, "A functional reference architecture for aggregators," in *Proc. IEEE 20th Conf. Emerg. Technol. Factory Autom. (ETFA)*, Sep. 2015, pp. 1–4.

[46] J. Pérez, J. Díaz, J. Garbajosa, A. Yagüe, E. Gonzalez, and M. Lopez-Perea, "Towards a reference architecture for large-scale smart grids system of systems," in *Proc. IEEE/ACM 3rd Int. Workshop Softw. Eng. Systems-of-Systems*, May 2015, pp. 5–11.

[47] M. Mylrea and S. N. G. Gourisetti, "Blockchain for smart grid resilience: Exchanging distributed energy at speed, scale and security," in *Proc. Resilience Week (RWS)*, 2017, pp. 1–9.

[48] P. Siano, G. De Marco, A. Rolán, and V. Loia, "A survey and evaluation of the potentials of distributed ledger technology for peer-to-peer transactive energy exchanges in local energy markets," *IEEE Syst. J.*, vol. 13, no. 3, pp. 3454–3466, Sep. 2019.

[49] *Event Report: Joining Forces for Blockchain Standardisation*, INATBA, Brussels, Belgium, Jun. 2020. [Online]. Available: https://ec.europa.eu/newsroom/dae/document.cfm?doc_id=68644

[50] *Joint Report: Joining Forces for Blockchain Standardisation*, INATBA Eur. Commission, Brussels, Belgium, Dec. 2021. [Online]. Available: https://inatba.org/reports/inatba-publishes-a-joint-report-with-the-european-commission-on-blockchain-standardisation/

[51] *C(2021) 7914 Final, Digital Europe: Work Programme 2021–2022*, Eur. Commission, Brussels, Belgium, Nov. 2021.

[52] *Blockchain and Distributed Ledger Technologies—Reference Architecture*, Standard ISO 23257, 1st ed. Feb. 2022.

[53] *Distributed Ledger Technology Reference Architecture*, Tech. Specification FG DLT D3.1, ITU-T, Geneva, Switzerland, Aug. 2019.

[54] *eIDAS Regulation. Regulation (EU) No 910/2014 of the European Parliament and of the Council of 23 July 2014 on Electronic Identification and Trust Services for Electronic Transactions in the Internal Market and Repealing Directive 1999/93/EC*, Eur. Parliament, Strasbourg, France, 2014.

[55] *Permissioned Distributed Ledger (PDL); Reference Architecture*, document ETSI GS PDL 012, May 2022.

[56] *IEEE Standard Association P2418.5 Working Group Y. IEEE SA P2418.5—Standard for Blockchain in Energy. IEEE Standard Association (Draft)*, Inst. Elect. Electron. Eng., Piscataway, NJ, USA, 2024.

[57] S. N. G. Gourisetti et al., "Standardization of the distributed ledger technology cybersecurity stack for power and energy applications," *Sustain. Energy, Grids Netw.*, vol. 28, Dec. 2021, Art. no. 100553.

[58] (Nov. 2012). *Smart Grid Reference Architecture CEN-CENELEC-ETSI Smart Grid Coordination Group*. [Online]. Available: https://ec.europa.eu/energy/sites/ener/files/documents/xpert_group1_reference_architecture.pdf

[59] C. Greer et al., "NIST framework and roadmap for smart grid interoperability standards, release 3.0," Nat. Inst. Standards Technol., Gaithersburg, MD, USA, Tech. Rep. NIST Special Publication 1108r3, 2014. [Online]. Available: https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=916755

[60] The GridWise Architecture Council. (Mar. 2008). *GridWise® Interoperability ContextSetting Framework*. [Online]. Available: https://gridwiseac.org/pdfs/GridWise_Interoperability_Context_Setting_Framework.pdf

[61] H. Zimmermann, "OSI reference model—The ISO model of architecture for open systems interconnection," *IEEE Trans. Commun.*, vol. COM-28, no. 4, pp. 425–432, Apr. 1980.

[62] C. Lima, "Developing open and interoperable DLT/blockchain standards," *Computer*, vol. 51, no. 11, pp. 106–111, Jan. 2019.

[63] *The IEEE DLT/Blockchain Reference Framework*, IEEE Standard 42010, Nov. 2022.

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