Blockchain Applications In Microgrids

An overview of current projects and concepts

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***Abstract*—Since the release of Bitcoins as crypto currency, Bitcoin has played a prominent part in the media. However, not Bitcoin but the underlying technology blockchain offers the possibility to innovatively change industries. The decentralized structure of the blockchain is particularly suitable for implementing control and business processes in microgrids, using smart contracts and decentralized applications. This paper provides a state of the art survey overview of current blockchain technology based projects with the potential to revolutionize microgrids and provides a first attempt to technically characterize different start-up approaches. The most promising use case from the microgrid perspective is peer-to-peer trading, where energy is exchanged and traded locally between consumers and prosumers. An application concept for distributed PV generation is provided in this promising area.**

***Index Terms*—Blockchain, Microgrid, P2P, Smart Contract**

I. Introduction

In 2008 the Bitcoin paper [1] was published by Satoshi Nakamoto, whose identity still remains a mystery. The goal of Bitcoin was to create a peer-to-peer (P2P) currency, that would remove the need for a trusted third party such as a bank. Since then, the media increasingly reported about Bitcoin due to the rise of the Bitcoin price, the revolutionary nature of the underlying blockchain technology and its abuse by criminals to transfer bitcoins in public without leaving physical traces. Transactions are only coupled with a Bitcoin address, which is not necessarily associated with an identity. In May 2017, the ransomware WannaCry, created by the NSA got loose and used an exploit in old Windows versions to infect computers all around the globe. The ransomware was able to acquire only 50 Bitcoins up to end of May 2017 [2] while another cryptomalware Erebus acquired even a Million US$ [3].

Apart from criminal uses, the underlying blockchain technology caught the attention of the financial sector in [4], which expects that the blockchain will disruptively change banking, insurance and asset management. The healthcare industry wants to use blockchains for safe storing and sharing of data. For supply chain management, various blockchain solutions are currently in development and governments investigate blockchains with regard to e-voting. The use cases of blockchain seem to be endless, as can be seen in [5].

Blockchain technology also caught the attention of the energy sector. The current electrical grids are evolving into Smart Grids, including growing amounts of sensors, information and communication technology, as well as acting electronic devices. On one side of the scale, super grids connecting different kinds of energy systems, which are traded as potential solution for large term storage challenges and on the other side, are microgrids, being considered "the" solution for integration of decentralized energy resources. Although this paper focuses on approaches instrumental to microgrids, some of the presented projects are simultaneously tackling super grid challenges as well. While microgrids offer advantages, such as reliability and cost-efficiency, several challenges need to be thoroughly researched and solved. Various approaches exist for implementing control and business processes in microgrids. One relatively new and very promising approach is using the blockchain. The decentralized structure of a blockchain is very suitable for implementing processes of energy systems as multi-agent system (MAS). This paper provides a brief technical background on the evolution of microgrids as well as the inner workings of blockchains before presenting a technical state-of-the-art survey on current blockchain projects for the energy sector, which have the potential to innovate microgrids. A concept for an application example in sharing photovoltaic (PV) generation and a discussion providing a glimpse on the direction of future research concludes this paper.

II. Background

A. Microgrid

A microgrid can be described as a cluster of loads, decentralized energy resources (DER) (e.g. PV panels, diesel generators) and energy storage systems (ESS) (e.g. battery, fly wheel), which are operated in coordination to supply electricity reliably. A microgrid might be connected at the point of common coupling to the distribution grid. Microgrids can be in four conditions: grid-connected, decoupling, island-mode, and recoupling. If a microgrid exchanges power with the distribution grid, it operates in grid-connected mode. In islanding or stand-alone mode, power is exchanged only locally between loads, DERs and ESSs. Microgrids are seen as an approach to reduce decentralized flexibility introduced by renewable energy sources through new control concepts. [6]

For controlling electric grids, there are two orthogonal approaches: centralized and decentralized control systems. In a centralized control system, an operator is responsible to run the entire system. Therefore, a very expensive and highly critical infrastructure of central control devices are required to process measured data and set appropriate actions. The control devices, their communication channels, and the information sent and received are thereby a multiple points of complete system failure. The current electricity grid control consists mostly of defined operators, operating the distribution grids, preferring the centralized control approach. On the contrary, in a decentralized control system every device controls itself independently, which increases the communication speed and fault-tolerance. Selfish decisions of the devices may affect the electric grid locally, but not as a whole. In [7] a roadmap for the transition from centralized to decentralized control systems was provided.

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A therein proposed system solution, capable of parallel operation with centralized control systems, is a distributed multi-agent based control system (DMACS). DMACS offer advantages, on multiple levels: meshing and autonomous switches vs. manual switches and open rings on distribution grid infrastructure level; dynamic MAS controlled storages assisting the grid vs. central storage power plants on prosumer level; scattered SCADA sensors vs. interoperable MAS integrated sensors and actuators with agent profiles on communication device level; power line communication vs. 5G Internet of Things on infrastructure technology level to list just a few. An over the lifecycle smaller environmental impact, economically beneficial probability as well as the promise of possible plug-&-play operation shown in [8] are additional intriguing arguments. Furthermore, these multi-agent approaches can be used for business processes in microgrids, like billing and pricing [9].

B. Blockchain

Blockchain is a distributed database called ledger in shape of chained data records called blocks. A block consists of an information and a linking part. The information part can contain various archetypal kinds of information such as financial records or transaction details but also computationally universal data-manipulation rules (aka. code), that can be interpreted, shared and accessed by everyone authorized. The linking part contains a link to the previous block in the chain, typically a computed hash value over the previous block. Due to chaining with hash functions cryptographic signature for linking the blocks, it can be ensured that signed blocks cannot be tampered without being recognized [1].

An important aspect in the use of blockchain technology are smart contracts and decentralized applications, which can be built on top of blockchains. Smart contracts are a method to form agreements through the blockchain. Ethereum, a decentralized platform that runs smart contracts and uses blockchain technology, has a built-in Turing-complete programming language, which can be used to write smart contracts and decentralized applications as stated in [10] [11].

C. Consensus Mechanisms

In traditional payments, third parties, traditionally banks, are trusted for maintaining transactions and account balances. In contrast, the blockchain is a trustless and distributed consensus system. Third-parties are not needed for transactions. Everyone can verify the written information, because everyone has a copy of the blockchain. It is important, that everyone has the same copy. To reach this system-wide consistent consensus, a consensus mechanism, either proof-of-work or proof-of-stake is needed. [1]

1) Proof-of-Work (PoW)

In the proof-of-work system, miners compete to solve a "computational puzzle", which is moderately hard to solve but the result should be easy to verify. This puzzle involves the determination of a nonce, that when the block data is hashed, the hash is smaller than a defined threshold. Usually brute force is used for solving the puzzle. This process is called mining. As the computing power of the network increases, blocks are created faster. Reacting to this change, the defined threshold, called difficulty, is periodically adapted to regulate the block generation rate. The first miner to find a solution advertises it to the network and is rewarded. The mining serves two purposes: to verify the legitimacy of transactions and to create new coins by rewarding miners. The disadvantage of PoW that a lot of energy is needed, e.g. Bitcoin transactions by 2020 will consume as much electricity as Denmark today [1] [12] [13].

2) Proof-of-Stake (PoS)

In the proof-of-stake system miners do not compete, instead a validator set is maintained. Anyone, who owns blockchain's coins, can join this set by locking all his coins, called the stake, into a deposit. The validators participate then in the block creation process, where two major types of consensus algorithms are used. In Chain-based PoS the validator, who has the right to create the block, is periodically pseudo-randomly selected. In Byzantine-fault-tolerant-style PoS the validators can propose blocks, the right to do so is randomly assigned to them, further the validators then agree or disagree on the proposed blocks by voting. The block creator gets transactions fees instead of block rewards. Therefore, all coins are created in the beginning, and their number never changes. As described in [12] [14], advantages of PoS are that less energy is needed for consensus and the increased protection against attacks.

3) Proof-of-Authority (PoA)

In the proof-of-authority system only authorized nodes exclusively have the right to create new blocks. The system does not rely on solving "computational puzzles" and is mostly used for consortium blockchains [15].

D. Blockchain Types

Based on access permissions and alteration capabilities, [16] [17] describe three different types of blockchains:

1) Public Blockchain

Public blockchains are considered to be open and "fully decentralized". Anyone is able to read the blockchain, send transactions and participate in the consensus process. To secure a public blockchain, consensus mechanisms are used. Due to the openness, trust and usage of these blockchains are higher.

2) Consortium Blockchain

Consortium blockchains are controlled by specific groups, where only a defined set of nodes participates in the consensus process. They are considered to be "partially decentralized". The right permission may be public or restricted. Advantages are that they are faster and provide more privacy. This type of blockchain is mostly used in the financial sector.

3) Private Blockchain

Private blockchains are usually owned by one person or company, who has write permission and verifies the transactions. The blockchain may be publicly accessible or not. Its advantages are: the blockchain is alterable (e.g. transactions can be reverted), the validators are known, no risk of a 51% attack, cheaper transactions, faster consensus algorithms possible and greater level of privacy if the read permissions are restricted. Mostly they are used for company internal processes like database management and auditing.

III. Blockchain Applications In Microgrids

The decentralized structure of blockchain fits into the decentralized approach for control and business processes in a microgrid. In this section, selected blockchain projects and concepts for microgrids are presented. Most projects are still under development or in testing phase, therefore projects with publicly available information were chosen primarily.

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1) PWR.Company

PWR.Company [18] focuses on P2P renewable energy trading in microgrids. Instead of selling the energy immediately, PWR equips households with deep cycle batteries for power storage to stabilize the grid. The project currently uses the Ethereum platform, which will be replaced in the future by their own version of an energy based cryptocurrency, the PWRToken. One PWRToken equals to 1 MWh and can be traded on various exchange markets.

2) PowerLedger

PowerLedger provides a market trading and clearing mechanism based on blockchain [19]. Owners of renewable energy sources can sell their surplus of energy at a chosen price within microgrids or over the distribution network. Distribution system operators (DSO) receive a revenue for energy traded over the distribution network.

3) Key2Energy

In the Key2Energy concept [20], instead of consuming power from the grid, multi-apartment houses provide self-generated PV energy to its tenants at cheaper costs. In this process two agents are involved. The first tries to maximize the revenues for the house by selling the produced solar energy on the local market at best possible prices. The second tries to minimize the cost for shared electricity, by e.g. powering elevators and lighting. The blockchain is used for transactions and smart contracts for the market logic.

4) LO3 Energy - TransActive Grid and Brooklyn Microgrid

LO3 Energy [21] developed the TransActive Grid platform, that is based on Ethereum and smart contracts. The platform aims at various business models for distributed grid and transactive energy space. It enables peer-to-peer energy transactions, control of DERs for grid balancing, demand response, emergency management and other uses. For this purpose, TransActive Grid elements (TAG-e) are developed, which consist of a computer and an electric meter. Their tasks are measuring the energy production and consumption, sharing this information with other TAG-e in the network and acting upon this information. The vision is to create a blockchain-based microgrid intelligence system. Another project is the Brooklyn Microgrid, a P2P energy market for locally generated renewable energy [22]. It focuses on the Brooklyn community, where participants can sell the surplus of produced solar energy to their neighbors.

5) Dajie

Dajie [23] provides IoT devices and a blockchain-based platform. To participate, users must install and register one of Dajie's IoT devices. The platform aims at the P2P energy exchange, to use coins to pay energy and services to energy companies and to redeem carbon credit with coins. Coins can be earned by producing energy. One coin equals 1kWh of produced energy.

6) Share&Charge

Share&Charge [24] is a network of electric vehicle (EV) charging stations. Owners of charging stations can register their station and set tariffs for charging. Before the registration, the station must be equipped with the Share&Charge module, which's aim is to prevent unauthorized use. EV owners can load their Share&Charge wallets with money. The billing of the charging at the station is handled by Share&Charge. Transactions and invoices are stored in the Share&Charge wallet and can there be monitored and tracked. The Ethereum platform is used in the transaction layer.

7) NRGcoin

NRGcoin [25] uses an energy based cryptocurrency in a framework combining smart contracts. The smart contracts framework is based on Ethereum. One NRGcoin is equivalent to one kWh, regardless of the retail value of electricity. A key difference in this platform is that the energy must be produced by renewable energy sources and consumed locally. The smart contract platform is used to process and pay all grid fees and taxes to the DSO. The same system is responsible to validate the reported production of energy by the local clients that not only consume, but also produce power (prosumers). During the validation phase, it is checked if the energy is consumed locally. If the validation is successful, the prosumer is rewarded with NRGcoins, which can be used to pay for future green energy consumption or sold on a currency market. Therefore, oversupply in the local area is not rewarded. On the currency market consumers can buy these NRGcoins to pay for the green energy, thereby they pay 1 NRGcoin per kWh. All types of renewable energy are supported, not only solar energy. For the operation of NRGcoin, gateway devices are required, which measure the electricity flows and communicate with the smart contract and exchange market.

8) GrünStromJeton

Another, still very conceptual framework based on Ethereum is GrünstromJeton [26]. which serves as a verified proof of the actual electricity mix used. Instead of feed energy, consumed energy is considered. One key component is the use of GrünstromIndex, which is an index that indicates the relative production of energy from alternative, "green" power sources in the next 36 hours. When this index is higher, the fraction of power produced from green sources to total energy produced is higher. The system observes the energy consumption of the customers with the use of smart meters and rewards them with GrünstromJetons when they consume power from alternative sources. Therefore, the higher the index, the more Jetons the consumer earns, which can be traded and exchanged.

9) SolarCoin

SolarCoin's aim is to enhance the production of solar energy [27]. Consumers are deterred to invest into solar installations due to long payback times. To reduce it, prosumers are rewarded one SolarCoin per produced MWh. With electricity meters, claims for SolarCoins are verified. To register solar installations, different affiliate facilitators exist: SolarChange, ElectriCChain, and SolCrypto.

10) TheSunExchange

TheSunExchange enables "crowd-sale", where users purchase solar cells and lease them to earn a passive income [28]. The project targets at developing countries, where government corruption is a major problem. The leasing user pays a rental, from which the solar cell owner receives a Bitcoin income for 20 years. Additionally, the owner earns SolarCoins for the lifespan of the project.

11) Bankymoon

Bankymoon [29] [30] offers prepaid meters, which are blockchain-aware. The idea is to enable funding of electricity, water, and gas to everybody in the world. The meters can be "loaded" by sending payments to the meter in different cryptocurrencies. The pilot project Usizo focuses thereby on needs of African schools, where users around the world can directly spend cryptocurrencies such as Bitcoins to the school's meter to fund e.g. electricity for a month.

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12) GridSingularity

GridSingularity [31] [32] develops a decentralized data exchange platform for the energy sector. The platform does not focus only on electricity but further on gas, heating, and water. The core of the concept is the "Turing Complete Energy Market Agent", a software agent that communicates at the household level to appliances and tries to optimize energy usage. The Agent focuses primarily on the distribution network, but can also be extended to the transmission network. The platform thereby hosts different applications to ease energy data analysis and benchmarking, smart grid management, trading of green certificates, investment decisions and energy trade validation. The user can choose whether one wants to use existing applications or develop own ones.

13) Electron

The UK-based company Electron develops Ethereum-based solutions for the energy sector, which work alongside existing systems [33]. The Meter Registration Platform is a shared registration platform for different types of assets like gas and electricity supply points, which enables switching the energy-supplier in near real-time. The Flexibility Trading Platform is an exchange platform for demand-side response actions, which enables collaborative trading comparable to P2P trading. Another focus lies on Smart Meter Data Privacy, with encryption techniques, which enable value extraction from smart meter data besides assuring user's data privacy. For the development of these products, several tools were built, which are available as open source.

14) PONTON Gridchain and Enerchain

PONTON, a German software company, researched the use of blockchain for grid process integration. The pilot software Gridchain simulates future processes for real-time grid management and achieves following results [34]: coordination of requests of balancing power between TSOs, DSOs, aggregators and generation units within seconds; interaction of DSOs with the balancing request process in congestion situations before the delivery period; signaling to aggregators about adjusting their merit order list depending on short-term load signal and down settlement time was reduced from ¿ 1 month to 15 minutes. Another project is Enerchain, a platform, which enables wholesale P2P energy trading over blockchain, where users can directly buy and sell energy. [35]

IV. Technical Overview

In Table I a summary of the mentioned projects by following technical properties is given: used/underlying blockchain, type of blockchain (public, private), consensus mechanism (PoW, PoS, PoA), project or parts available as open source and hardware development included in project. The following notation is used in Table I: "X" (attribute applies), "-" (attribute does not apply) and "/" (no information available). For Key2Energy, Dajie, PONTON Gridchain and Enerchain no information about the technical realization was available and therefore these projects are not listed in Table I.

PowerLedger uses the private Ethereum blockchain with PoW and the public self-developed Ecochain with PoS. The project will be published open source. Hardware development is not the company's preference, but possible if required. [36]

Share&Charge utilizes the public Ethereum blockchain, which provides PoW as consensus mechanism. The application binary interfaces to interact with the implemented smart contracts are available. The sources of these contracts will be published on GitHub after completing ongoing security audits. The developed Share&Charge module can be used to upgrade existing charging stations for the integration into the Share&Charge network. [37]

NRGcoin is currently at the conceptual stage, where it is exploring different possibilities for implementation such as existing and custom blockchains before committing to one. Whether and which parts of the project will be released open source is still unknown, due to an intended commercialization by the commercial partner Enervalis, which develops the needed "gateway devices". [38]

GrünStromJeton utilizes a public modified version of the Ethereum blockchain. Thereby, PoA is used as consensus mechanism with a private governance structure. The project is for the most part available open source and the hardware development is co-operated with various partners. [39]

GridSingulartiy currently uses public Ethereum blockchains with PoW and PoA. However, after the Energy Web Foundation (EWF) blockchain is published, it is to be moved to this. The EWF blockchain will then be available via EWF as open source. Hardware development is not planned. [40]

Following projects are based on Ethereum, which currently works with PoW: PWR.Company, TransActiveGrid (includes development of TAG-e), Brooklyn Microgrid, Dajie (includes development of IoT devices), Electron and TheSunExchange. Bankymoon uses Bitcoin with PoW and develops own smart meters. SolarCoin uses Litecoin with PoW.

V. Application Concept Of Sharing Distributed PV Generation

Blockchain is regarded as promising innovative technology which by nature lends itself to being combined with decentralized control systems, decentralized algorithms, and machine learning. This application concept describes the goal to optimize the energy usage of energy generated by PV systems combined with ESSs across a microgrid community of several buildings or even at municipal scale.

A typical family house of this community would be equipped with a PV system, a heat pump, a hot water storage system and multiple sensors. The described concept application intends to identify the technically possible optimal usage of different systems (heating, cooling, hot water storage, ESS) in combination with short-term weather forecasts and machine learning driven energy consumption prediction. The results can be applied to groups of different buildings and individual building data collected to let machine learned models adjust. Using proper interfaces, it is possible to combine data collected from real buildings, to create a simulation environment. In this environment, various strategies based on distributed algorithms or agent systems can be tested and aim at optimizing the total energy consumption in the whole community. Each prosumer constitutes a different client system, with different constrains, needs, and priorities. These clients have individual systems (heating, cooling, hot water storage, ESS) that are controlled with the goal of achieving a (close to) optimal energy consumption locally (local optimum solution). However, very often the synergetic use of the total resources available to a group or subgroup of prosumers can lead to an overall better solution, which provides a smaller total grid consumption, without compromising the limitations and

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TABLE I
TECHNICAL COMPARISON

Projects	Technical Parameters				
	Blockchain	***Blockchain type***	***Consensus mechanism***	***Open source***	***Hardware development***
PWR.Company TransActiveGrid TheSunExchange	Ethereum	/	PoW	/	X
PowerLedger	EcoChain Ethereum	Public Private	PoW PoS	X	X
BrooklynMicrogrid	Ethereum	/	PoW	/	/
Share&Charge	Ethereum	Public	PoS	X	X
NRGcoin	various	Public Private	various	X	X
GrünStromJeton	Ethereum	Public Private	PoA	X	X
SolarCoin	Litecoin	Public	PoW	/	/
Bankymoon	Bitcoin	Public	PoW	/	X
GridSingularity	Ethereum EWF	Public	PoW PoA	X	-
Electron	Ethereum	/	PoW	X	/

needs of individual systems (global optimum solution). To achieve this, a resilient and tamper-secure system for information transfer within the group is required, hence, the suggesting use of blockchain.

Blockchain as technology allows to transfer unaltered, information reliably between clients. This information can be used to optimize global targets (minimization of grid electricity consumption, reduction of transmission losses, increase of predictability and therefore economic gains in electricity markets or by delaying investments) and utilize the available systems of the prosumer communities, considering a multitude of parameters that affect the optimal state. These parameters could also include life-cycle and service cost of systems (e.g. battery storage systems) or virtual costs of energy transmission between neighbours. The use of sophisticated distributed algorithms, machine learning algorithms, and software agents can be used to automate the configuration of the individual components. To minimize privacy concerns of all prosumer data being recorded in public blockchains, this concept suggests designing blockchain technology based systems with privacy-by-design principles in mind. A first attempt adapting these principles for distributed databases could include: transferring only minimum amounts of information into the distributed database, trying to aggregate data wherever possible, and encrypted non-public data as soon as possible.

During the concept, the potential effect of the distributed ESSs to reduce flexibility and smooth electrical grid loads can be evaluated. All the different optimization strategies can be compared to results derived from round robin switching weeks to systems that optimize individual energy consumption and quantify the benefits. To evaluate the degree of optimization, the needs and priorities of different user communities must be collected and considered. As a result, it would be possible to create a list of recommendations for potential stakeholders (technology providers, end users, municipalities, grid operators) so that proper technical or legal frameworks to optimize energy usage efficiency can be established.

VI. CONCLUSION AND OUTLOOK

Blockchain technology is a promising innovation, which can be used in different microgrid areas. Probably the most popular use case application is P2P trading, where the blockchain enables energy trading between peers in a secure way. Thereby, different scenarios can be realized: community energy markets, like the Brooklyn Microgrid, where residents trade energy among themselves, energy selling house, like in the Key2Energy concept, which provides produced energy at a cheaper cost to its tenants and electric vehicle charging networks, like Share&Charge, where public and private charging stations are provided.

Other projects aim at increasing the use of renewable energy sources by rewarding the production or use of renewable energy. NRGcoin rewards injected renewable energy per kWh if it matches local demand. GrünStromJeton verifies the used electricity mix and rewards the consumers if energy from renewable sources is used. SolarCoin recompenses solar installation owners per produced MWh.

Blockchain-based prepaid meters, which can be remotely "loaded" with cryptocurrency, like Bankymoon's meters, are mainly interesting for African countries that are already deploying prepaid meters. But the idea can be applied globally, e.g. parents can "donate" energy to their children living abroad. Blockchain-crowdfunding as shown in TheSunExchanges idea, where solar cells are bought by users and then leased to others, could facilitate the electrification of rural areas without access to the main grid, where residents do not have the possibilities to invest huge amounts of money.

For DSOs, particularly PONTON's Gridchain, which facilitates the balancing request processes, and Electron's meter registration platform could be of interest. GridSingularity's decentralized data exchange platform, could provide a basis for all these use cases. On top of the platform different applications could be built, ranging from P2P trading to registration platforms.

Most projects are based on Ethereum, which offers the possibility of smart contract implementations. Currently Ethereum utilizes PoW as consensus mechanism. Due to security and scalability problems, Ethereum plans on changing the consensus mechanism to PoS. [41] Whether or how this will affect presented projects is not predictable.

Still, before operating on large scale, issues like regulation and scalability must be solved. The rising number of companies getting active could result in the use of plenty of different private and public

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blockchains, which could lead to interoperability and cybersecurity issues. Interoperability between different blockchains could be enabled with e.g. multi-chain frameworks like Parity's Polkadot [42], but being able to harden a small blockchain realization against a nation state driven 50% takeover attack is unlikely.

Consortia and organizations for cooperation between companies, DSOs, TSOs, and national governments are needed. The Energy Web Foundation (EWF) [43] is a non-profit organization co-created by GridSingularity and the Rocky Mountain Institute. Its goal is to accelerate the blockchain technology across the energy sector. Besides the development of an open-source IT infrastructure, including the EWF blockchain, different use cases are analyzed and pushed into proof of concepts and commercial applications. The EWF cooperates with a broad range of partners from the energy sector, regulators and standardization bodies.

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