Master Thesis

Open Blockchain-based Local Energy Market Simulation Platform

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1 Research Motivation

The generation from distributed renewable energy sources (RES) is constantly increasing [13]. In contrast to power plants which run by non-renewable fossil fuels, distributed RES produce energy in a decentralized and volatile way, which is hard to predict. These characteristics of the distributed RES challenge the current energy system [3].

The existing electric grid is build for centralized generation by large power plants and the design of the current wholesale markets is not able to react in real-time to a significant amount of distributed RES [13] [3]. Moreover, this way of energy generation is economically not ideal because of energy losses due to long physical distances between generation and consumption parties.

Therefore, new market approaches are needed, to successfully integrate the increasing amount of distributed RES [12]. A possible solution to the technical and market problems is Peer-to-Peer (P2P) energy trading in local energy markets (LEM) [10].

LEM, also called microgrid energy markets, consist of small scale prosumers, consumers and a market platform which enables the trading of locally generated energy between the parties of a community. Due to the trading of locally generated energy within the related communities, LEM support sustainability and an efficient use of distributed renewable energy sources. Likewise, the need of expensive and inefficient transportation of energy through long physical distances can be reduced. The concept of LEM strengthens the self-sufficiency of communities and enables possible energy cost reductions. Moreover, profits remain within the communities whereby reinvestments in additional RES are promoted [13].

However, P2P energy trading in LEM requires advanced communication and data exchanges between the different parties, which makes central management and operation more and more challenging. The implementation of LEM needs local distributed control and management techniques. [4]. Therefore, a new and innovative information communication technology (ICT) is required. A possible solution provides the emerging distributed ledger technology (DLT). It is designed to enable distributed transactions without a central trusted entity. Furthermore, an Ethereum-based blockchain allows the automated execution of smart contracts depending on vesting conditions, which suits the need of LEM for decentralized and autonomous market mechanisms. This offers new approaches and market designs. Accordingly, DLT can help addressing the challenges faced by decentralized energy systems. However, DLTs are not a matured technology yet and there are several barriers in using them, especially for researcher who do not have a technically background.

In addition, Ketter, Peters, Collins and Gupta introduce the approach of Competitive Benchmarking (CB) [9]. This approach describes a research method which faces a real world wicked problem that is beyond the capacity of a single discipline. This is realized by developing a shared paradigm which is represented in a concrete open simulation platform. In detail, it consists of the three principal elements *CB Alignment*, *CB Platform* and *CB Process*. The *CB Alignment* refers to the constant synchronization process between the shared paradigm and the wicked problem. Further, the *CB Platform* represents the medium, in which the shared paradigm is technically illustrated. In addition, the *CB Platform* provides the infrastructure for the third element *CB Process*. It describes the iterative development of new theories and design artifacts through independent researchers, which influence each other and improving their work in direct sight of each other.

Due to the plurality of involved parties and the interdisciplinary requirements for the implementation of new energy market approaches, the accessibility is of major importance. Therefore, the presence of such a open simulation platform depicting the shared paradigm of a LEM, would ensure the accessibility and could help to gain new valuable outcomes in the research field of LEM or new energy market designs in general.

Further, Guo, Koehler and Whinston developed a market-based optimization algorithm, which solves a distributed system optimization problem by self-interested agents iteratively trading bundled resources in a double auction market run by a dealer. The authors called it bundle trading market framework or short BTM [7]. The central problem of the stated market-based optimization algorithm can interpreted as the welfare optimization of all participants in a LEM. The dealer, which runs the double auction market, maximizes the welfare through allowing agents to trade their preferable bundles of energy. Hence, the stated BTM implemented on basis of a blockchain as underlying ICT can depict the concept of a LEM.

Consequently, this research will bring all the introduced approaches together and develop an open blockchain-based LEM simulation, which enables the research approach based on the three stated elements of CB. The platform will be realized through the introduced optimization algorithm with a blockchain as the underlying ICT. That means, the smart contract takes the role of the market dealer and the self-interested agents represent the individual participants in a LEM. The focus of this paper will be on the implementation and software design of the open blockchain-based LEM simulation platform.

2 Literature Review

2.1 Blockchain-based Energy Markets

To start off, Mihaylov et al. were the first who adressed blockchain technology in energy markets. They present a new decentralized digital currency with the aid of which prosumers trade locally produced renewable energy [14]. In their introduced concept, the generation and consumption of renewable energy is direct transferable into virtual coins. However, the market value of the virtual currency is determined centrally by the distributed system operator. Further, Al Kawasmi et al. introduce a blockchain-based model for a decentralized carbon emission trading infrastructure [2]. Their model based on the bitcoin protocol and focus on privacy and system security goals. Besides, they provide a solution to the problem of anonymous carbon emission trading. Equally, Aitzhan and Svetinovic address the issue of transaction security in decentralized smart grid energy trading and implemented a proof-of-concept for a blockchain-based energy trading system including anonymous encrypted messaging streams [1]. Concluding, they show that blockchains enable the implementation of decentralized energy trading and that the degree of privacy and security is higher than in traditional centralized trading platforms. Furthermore, Sikorski et al. present an proof-of-concept where a blockchain enables machine-to-machine (M2M) interactions depicting an M2M energy market [15]. They pointed out that the blockchain technology has significant potential to support and enhance the 4th industrial revolution. Moreover, Mengelkamp et al. reveal the concept of a blockchain-based local energy market without the need of a thrusted third entity [13]. In addition, they deduce seven market components as a framework for building efficient microgrid energy markets. Consequently, the Brooklyn Microgrid project is introduced and evaluated according the market components. As a result, the Brooklyn Microgrid also shows that blockchains are a suitable technology to implement decentralized microgrid energy markets, though current regulation does not allow to run such a local energy markets in most of the countries. Later on, Mengelkamp et al. present an initial proof-of-concept of a simple blockchain-based concept, market design and simulation of a local energy market consisting of hundred households [12]. Finally, they conclude that the real-life realisation and technological limitations of such blockchain-based market approaches need to be investigated by further research. In addition, it is mentioned that regulatory changes will play an important role in the future of blockchain-based LEM.

2.2 Distributed Resource Optimization

To begin with, Fan et al. outline a new approach for the development of an information system which can be used for the problem of a supply chain. The concept demonstrate a decentralized decision making process that is realized through the design of a market-based coordination system which incite the pariticipants to act in a way that is beneficial to the overall systems [5]. Further, Guo et al. revive this concept and develop a market-based decomposition method for decomposable linear systems, that can be easily implemented to support real-time optimization of dsitributed systems [7]. They prove that the system optimality can be achieved under a dynamic market-trading algorithm in a finite number of trades. Moreover, the outlined alogrithm can be operated in synchronous and as well in asynchronous environments. Later on, Guo et al. extend their stated concept to a dynamic, asynchronous internet market environment [6]. Additionally, they examine how various market design factors like dealer inventory policies, market communication patterns, and agent learning strategies affect the computational market efficiency and implementation. Finally, also this time, Guo et al. prove finite convergence to an optimal solution under all these different schemes.

2.3 Competitive Benchmarking

Firstly, March and Smith describe a two dimensional framework for research in IS [11]. The two dimensions can be distinguished into behavioral-science and design-science. The behavioral-science paradigm is based on explaining or predicting human or organizational behavior. Whereas, the design-science paradigm is based on broad types of outputs produced by design research. It strives to extend the boundaries of human and organizational capabilities through the creation of new artifacts.

Furthermore, the research framework presented by Hevner et al. combines the both stated IT research paradigms and illustrates the interaction between these two [8]. They present that the technology and behavior are inseparable in an information system. Therefore, they argue that considering the complementary research cycle between design-science and behavioral-science is crucial to address fundamental problems faced in the productive application of information technology.

In addition, Ketter, Peters, Collins and Gupta introduce the IS research approach called Competitive Benchmarking (CB), which includes varios basic principles of the design science approach of Hevner et al. [9]. This IS research concept is designed for so called wicked problems and address the problems and needs of interdisciplinary research communities. CB focus on the interconnection of problems at the same and different levels to imitate real world. In repeated competitions, in which individual teams compete against each other, the developed environment and models can be tested and evaluated. This results in a diversity of outcoming designs, which are difficult to achieve in traditional design science frameworks.

3 Research Design

This research is inspired by the stated CB research approach and focus on the development of the second CB element, an open simulation platform depicting the shared paradigm of a LEM. The proposed design is presented in Figure 1. In contrast to the inital CB research design, the third element *CB Process* differs. The paltform enables research groups to design and test their artifacts in the field of the shared paradigm, using the developed platform. However, the designed artifacts in the form of autonomous software agents do not compete against each other in competitions. Rather, research groups are able to design and develop the behavior of all agents and the autonomous market mechanism. Hence, it is also possible to analyze and evaluate the designed artifacts and use them as a benchmark to compare different designs.

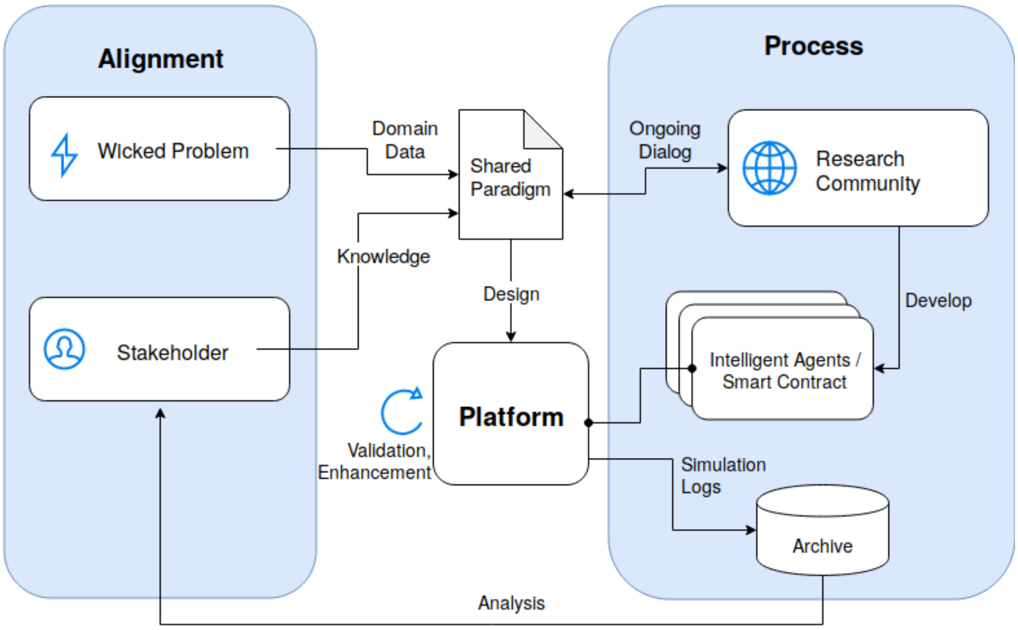

Figure 1: Research Design following Ketter, Peters, Collins and Gupta [9]

According to the IS Design Science principles introduced by Hevner, March, Park, and Ram [8], the presented research design produce a viable artifact in the form of an open simulation platform, which depict a relevant real-world wicked problem. Due to the outcoming data produced by the simulation platform, it is possible to develop methods to evaluate the utility, quality and efficacy of the artifact. Moreover, the research provide a varifable contribution through the artifact, the open simulation platform, itself. The platform enables the investigation of possible solutions of unsolved problems and further, it removes the technical barriers for the use of the complex distributed ledger technology. Besides, the implementation of the platform is based on an appropriate selection of techniques. As stated in 2.1, blockchains are a suitable technology to implement decentralized microgrid energy markets. In addition, the in 2.2 introduced distributed optimization algorithm achieve evidentially system optimality under a dynamic market-trading algorithm. Therefore, this research relies upon the application of rigorous methods and comply the requirement of the fifth guideline by Hevner et al. [8]. In addition, the platform enables the iterative search for an optimal design through the comparison of different produced solutions and is valuable to technology-oriented as well as management-oriented audiences. As a result, these research design also fulfil the seven research guidlines of the research framework introduced by Hevner et al. [8].

4 Expected Contribution

This research provides two different contributions. First, the fully decentralization of the introduced distributed optimization algorithm [7]. The bundle-trading market grant access of any given trade to the market dealer. This, again, necessitates trust of the agents that it will use those resources according to the over-arching organizational goal. Due to the implementation of the market dealer by a smart contract, the technical implementation is public accesible. Moreover, all transactions of the market dealer to allocate the resources are transparent. Therefore, the behavior of the market dealer is comprehensible for every participant. Furthermore, it provides a high degree of security due to cryptographic encryption methods which are essential parts of the blockchain. Second, the open simulation platform itself. From the scientific perspective, the platform is relevant due to the removal of existing technical barriers for practicioners in using complex distributed ledgers technologies. Therefore the platform facilitates researchers without a deep technically background to use those DLTs and incentivises to design and test their artifacts by using this platform. On the other hand, from a business perspective, this research is relevant to policy makers and energy suppliers. The platform allows stakeholders to get a better understanding of the dynamics of decentralized LEM and enables the testing and evaluating of policy options and implications.

5 Simulation Platform Architecture

This chapter gives a short representation of the first platform design and the chosen technologies and frameworks. First, the Ethereum blockchain is implemented through Ganache. It is a personal local blockchain for the Ethereum development, which can be used to deploy smart contracts, develop decentralized applications, and run tests. Further, Ganache is available as a desktop application as well as a command-line tool. Next, the role of the market dealer is realized by a smart contract which is written in Solidity. This object-oriented programming language was especially designed for developing smart contracts that run on a Ethereum blockchain. The Solidity code is compiled to bytecode, which can be deployed into the blockchain. Moreover, the clients which constitute the different agents are implemented through the programming language Python. Python is a object oriented, high-level programming language with a easy and simple to learn syntax. Therefore, the hurdles in modifying the client behavior are minimized. Finally, the clients using the Web3.py python library for the interaction with the Ethereum blockchain.

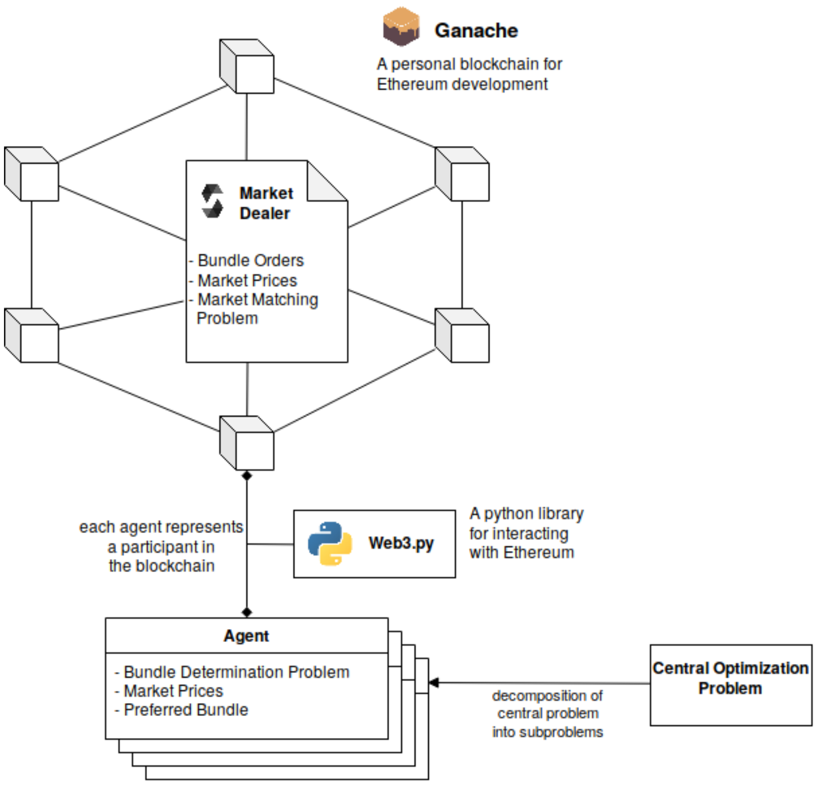

Figure 2: Platform Design

6 About Blockchain

To begin with, this chapter will give an overview of the general purpose, the contained components and the fundamental functionality of a blockchain.

6.1 General Purpose

In general, a blockchain can be described as a digital data structure that can be understand as a shared and distributed database, containing a continuous expanding and chronological log of transactions [4]. Besides, various types like digital transactions, data records and executables can be stored in this digital data structure. The data transmission in a blockchain is comparable with copying data from one computer to another. However, the resulting challenge is that the system needs to ensure that the data is copied just once [4]. For example, in the domain of cryptocurrencies, this is equal to sending a coin from one wallet to another. In this case, the system needs to validate that this coin is spended just once and there is no double-spending. A conventional solution for this problem is a third intermediary. To come back to the stated example, the third intermediary is represented by a traditional bank, which store, protect and continuously update the valid state of the ledger [4]. But, in some cases central management is not practicable or reasonable. Reasons for this are possible intermediary costs or a high degree of trust of the users into the intermediary who operates the system. Further, central management has a significant disadvantage because of a single point of failure. Hence, the centralized system is fragile to technical problems as well to external malicious attacks [4]. Consequently, the main reason of bockchain technologies is the removal of such third trusted intermediaries through a distributed network of various users, who cooperating together to verify transactions and protect the validity of the ledger

6.2 Architecture

This subsection covers the architectural design of a blockchain and presents all contained components in detail. Due to the plurality of the blockchain technologies, each of the technology slightly differs in design and components. The following explanations are oriented torwards the Ethereum blockchain implementation, which is also used as the underlying ICT to implement the open simulation platform.

6.2.1 The World State

Referring to the *Yellow Paper* [16], Ethereum can be seen as a transaction based state machine

6.2.2 The Block

To begin with, a blockchain is a sequence of blocks, which holds a complete list of transaction records [17]. However, what is a block, which informations are contained, and and how arises a chain out of the various single blocks? This questions will be adressed in the following part. A block is a collection of different relevant informations and consists of the *block header* and the contained transactions. Following *Ethereums Yellow Paper* [16], the subsequent pieces of information are contained in the *block header*:

Parent Hash: This is the Keccak-256 hash of the parents block's header

Beneficiary: The miners address (20-byte) to which all block rewards from the successful mining of a block are transferred.

State Root: This is the Keccak-256 hash of the root node of the state trie, after a block and its transactions are finalized. The state trie is the one and only global state in the Ethereum world. It is used as a secure unqiue identifier for the state and the state root node is cryptographically dependent on all internal state trie data.

Transactions Root: This is the Keccak-256 hash of the root node of the transaction trie. This trie contains all transactions in the block body and there is a separate transactions trie for every block.

Receipts Root: Every time a transaction is executed, Ethereum generates a transaction receipt that contains information about the transaction execution. This field is the Keccak-256 hash of the root node of the transactions receipt trie.

Difficulty: This is a measure of how hard it was to mine this block – a quantity calculated from the previous block's difficulty and its timestamp

Number: This is a quantity equal to the number of blocks that precede the current block in the blockchain.

Gas Limit: This is a quantity equal to the current maximum gas expenditure per block. Each transaction consumes gas. The gas limit specifies the maximum gas that can be used by the transactions included in the block. It is a way to limit the number of transactions in a block.

Gas Used: This is a quantity equal to the total gas used in transactions in this block.

Timestamp: This is a record of Unix's time at this block's inception.

Nonce: This is an 8-byte hash that verifies a sufficient amount of computation has been done on this block. Further, it is a number added to a hashed block that, when rehashed, meets the difficulty level restrictions. The nonce is the number that blockchain miners are solving for.

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