Power Share - Blockchain Management System and P2P Energy Trading

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Abstract

Blockchain is a technology that could innovate the energy sector since it can manage, store and certify data with no need for an external service provider. Power Share combines the use of an Eco-Feedback system with Blockchain technology, allowing the users to sell and buy energy from their neighbours at better rates, instead of selling the energy to normal energy operators, challenging this way the current energy supply system and making the market more competitive. Connecting local prosumers and consumers also helps reduce the system's costs and improve grid stability through better management of the supply. This solution consists on the implementation of a better performing and more efficient blockchain technology, based on Hyperledger Fabric, and the updating of the previously developed android app to work with the new environment.

Keywords: Blockchain; Peer-to-peer energy trading; Distributed ledger; IBM Hyperledger; Renewable energy.

1. Introduction

In the 21st century, the growing increase in energy consumption and the constant emission of polluting gases are still problems to be solved. Clean and renewable energy sources are increasingly being used to replace fossil fuels, nevertheless, they are not enough to meet the world's energy demand. Thus, increasing efficiency and reducing energy waste is more important than ever before. To face the current energy crisis and reduce the environmental impact of energy production and consumption, both prosumers - "energy consumers who also produce their own energy from a range of different onsite generators; mainly from renewable energy sources." [3] - and consumers are being asked to play an increasingly active role in the management and monitoring of their consumption. Several are the solutions developed specifically to support people in performing this task and, among them, it is worth mentioning the eco-feedback technology, which aims to provide "feedback on individual or group behaviours with a goal of reducing environmental impact [7], and Distributed ledger technologies. In addition, these technologies, and especially blockchain, are gaining increasing attention into the energy sector, where their most promising applications seem to be P2P energy trading and energy supply certification. Thanks to such technologies, energy consumers and prosumers can now buy and sell energy between each other. For prosumers, this means having an alternative to selling the excedent energy to the electricity company at a very low fixed-rate (feed-in tariff). While consumers that don't have their own energy generation system could buy local, green energy, at a lower rate, directly from those producers that are available to sell their excedent energy. It is not only prosumers and consumers that could benefit from the integration of blockchain in smart grids but also transmission system operators, as using blockchains together with smart meters installed in each household would make billing and metering processes faster and automated [9]. Despite their clear potential, blockchain is still a "new" technologiy, thus a lot of work still needs to be done in order to get a better understanding of their application in energy trading.

1.1. Objectives

The peer-to-peer network developed in the scope of the previous master thesis [4] was deployed in Madeira Island and used to simulate the energy trading within a small neighbourhood community. Payments were performed using the IOTA network and energy was exchanged by means of its cryptocurrency (mIOTA). Despite its theoretical advantages, results from the previous study showed several limitations of such technology, leading to conclude that, in its current state, IOTA is not suitable for Energy Trading where the server that managed the payment network had a very high energy consumption and transaction speed was much lower than expected, affecting the user experience of the trading system. The main objective was then develop a new blockchain-based, improved version of the previous system with focus on transaction automation, performance and server energy efficiency.

1.2. Proposed Approach

The expected result of this work will be the release of a new version of the android app and trading server based on the research of the most recent advances in blockchain technology. The server that provides the REST API to the android app will be reviewed and adapted to work seamlessly with the new blockchain system. The blockchain system will have an admin interface where the blockchain operator could test the network transactions, check all the assets and participants in the network. To evaluate the proposed solution, a second pilot was deployed in Madeira involving the same sample that took part in the field-test of Power Share. At the end of the study, results will be compared with those from the first deployment and conclusions will be elaborated.

2. Related Work

This chapter presents some background and related work on blockchain technologies and its applications in the energy sector. The previous work developed on the Power Share system is also briefly described here.

2.1. Power Share version 1

Power Share is a Peer-to-Peer energy trading system resulting from the previous master thesis [4]. It mainly consists of an Android application connected with an Energy Trading Management System (ETMS), that performs payments via IOTA and contemporary provides Eco-Feedback using production and consumption data collected through the smart meters installed in the houses of participants in the project. Data from the smart meters are collected in a server that is also responsible for managing energy offer and demand on the peer-to-peer network, providing users with feedback on their energy consumption and production data and managing their account settings (figure 1).

Power Share users are able to simulate energy transactions within the app and define energy buying and/or selling criteria. “Ranking” is the another section of the app, which presents the top ten users that, each week, have consumed (in percentage) the most energy from renewable sources. Alongside the android app, a java with Spring framework web server was created to handle the API requests from the android app and receive the readings of energy production and consumption from the smart meters [4].

Figure 1: Power Share home screen and energy data

The energy trading algorithm in the trading server was another important feature of this system and consists of three main asynchronous tasks:

- Start Transactions: where all the users that want to sell and/or buy energy are analyzed and, if a match between a seller and buyer settings is found, a temporary transaction is created between the two users;
- Verify Transactions: Every two minutes the system analyses the list of temporary transactions and verifies if the energy exchanged is greater than zero. If after 5 minutes the amount of energy exchanged is still zero, the transaction is stopped and both buyer and seller entries are updated into the database;
- Stop Transactions: The ETMS will be checking the temporary transactions and, after an hour of successful energy trading, these transactions are terminated. A final transaction is then created in the database with the total energy exchanged during the one hour period. Both buyer and seller data are updated and available to start a new transaction.

For the purpose of this project, IOTA cryptocurrency - mIOTA, a tangle based cryptocurrency that aims to provide a safe and decentralized financial ecosystem for the IoT [16] - was used as a mean of exchange for energy. Payments were performed each time a final energy transaction is made on the ETMS.Despite the theoretical advantages of the implemented blockchain [15], the main benefits that blockchain technologies could bring - like the automation of transactions using Decentralized apps and smart contracts (described in the following pages) - were not implemented in this version. Moreover, at the end of the deployment, several drawbacks of using IOTA technology emerged. Among them the system power consumption, issues related to the addresses' generation process and the unexpected length of the transactions' validation process (i.e. synchronization and latency of transaction propagation), that negatively affected the user experience.

2.2. Blockchain Technology
Blockchain is a secure and transparent distributed ledger technology used for the transmission and storage of data. It relies on a decentralized system, a peer-to-peer network of interconnected computers, which does not require a central supervising authority. This technology was first proposed in 2008 by Satoshi Nakamoto (pseudonym of the person or group of people who created Bitcoin), that published the Bitcoin white paper [14] describing the first digital currency developed to allow peer-to-peer payments and solve the double-spending problem in a decentralized fashion without the need of a central trusted party. This techonology also enables trustless networks, where 'trustless' means that all the parties could make transactions without the need to trust each other. This is possible thanks to the use of cryptography, which brings authoritativeness behind all the interactions in the network. The use of cryptography, however, doesn't completely eliminate trust in the system but it minimizes the amount of trust required from any single participant by running an economic game that incentivizes participants to cooperate with the rules defined by the blockchain protocol.

Blockchains can also have different access restrictions, which distinguish between Permissionless blockchains and Permissioned blockchains [19]:

- Permissionless Blockchains, also known as public blockchains, don't require any authorization to, read and write data on the blockchain. In other words, there isn't any kind of censorship on permissionless blockchains, any party in the network can read from the ledger and/or create a wallet and make transactions [14, 1]. Moreover, any user can run a validation node and purchase mining rights to support the blockchain operations. In these networks, validators are normally rewarded for their contribution. Bitcoin and Ethereum are the most famous networks that use a public blockchain;

- Permissioned Blockchains, also known as private blockchains, users require some sort of permission or authorization to access some (if not all) parts of the blockchain and only trusted nodes are allowed to verify the transactions [18, 1]. These kinds of blockchains are normally used by companies to securely record transactions or exchange data between each other. Permissioned blockchains are also considered more strict and controlled systems since all the participants in the network are whitelisted and bounded by strict contractual obligations to behave "correctly".

Consensus algorithms are the mechanism that provides security in a blockchain by ensuring that no malicious transactions or changes can be made on the blockchain, that is to say, guaranteeing "that the nodes agree on a unique order in which entries are appended"[1]. A brief description of the major validation mechanisms on blockchains is made:

- Proof of Work (PoW) is used in the bitcoin [14] where network participants (also known as miners [8]) compete with each other to add the next transaction block to a blockchain by solving a complex cryptographic puzzle, which leads them to validate prior transactions in the process and earning transaction fees for their work. This consensus protocol is the most widely used in the blockchain ecosystem. Nonetheless, PoW validation process is highly demanding in terms of energy and computational power;

- With Proof of Stake (PoS), the validation process is different. Network validators are connected to each other with servers and they invest in tokens or cryptocurrencies in the blockchain network, representing their stake in the block.PoS attempts to solve the energy expenditure problem created by PoW. Compared to the PoW mechanism, PoS system is by design less energy-intensive because there's no mining involved, requiring much less computer power to validate a transaction [12].

- The Delegated Proof of Stake DPoS uses real-time voting combined with a social system of reputation to achieve consensus. In DPoS every token holder can vote for the blockchain main elected delegates. In this protocol, block producers can collaborate to add blocks in the blockchain instead of competing like in PoW and PoS. DPoS is considered to be a more centralized blockchain consensus protocol, however, it's more efficient and it could reach much faster block times than the other PoW or PoS mechanisms.

- Practical Byzantine Fault Tolerance PBFT solves a classical problem (the Byzantine Generals Problem [13]) in distributed computing where a group of nodes communicate with each other in order to reach consensus. Based on signed messages and partially synchronous network, the PBFT consensus algorithm is capable of handling malfunctioning nodes and generating consensus in one of those environments [2].

- Proof of Authority is a consensus algorithm with better performance than BFT algorithms resulting from lighter message exchanges [6]. With this algorithm, transactions are validated by pre-selected authorities (named validators). These nodes are the authority of the blockchain system and new blocks are created only when the majority of them reach a consensus. The PoA creates a very centralized system but it is easily scalable and allows a very high transaction throughput.

In the context of this research, the most well-known and widely used blockchains for smart contract development are Hyperledger Fabric, Ethereum and EOS.

2.3. Blockchain Technology in the Energy Sector

Blockchain is not yet a mature technology, thus it still needs to be fully adopted and understood. Nowadays, the most advanced applications of this technology can be found in the finance industry, nevertheless, its disruptive potential is finally being explored also in the energy sector. This technology has the potential to disrupt the current energy market by creating a new decentralized, democratized, transparent and more efficient energy supply systems. Nowadays, the energy market is a monopoly controlled by the main distribution companies and there is no transparency in the way they operate. Energy prosumers have difficulties selling their surplus energy at a fair price because most of the times it can be sold only to the electricity company at a fixed (and usually quite low) tariff, while consumers can only buy energy from the grid operator, and without any guarantees that it comes from a renewable energy source.

Blockchain emerges as a possible workaround for these issues since it provides a secure, decentralized, peer-to-peer network where smart contracts would automate transactions, thus ensuring information integrity, transparency, and confidence between all parties [17]. In addition, payments could be made via cryptocurrencies, leading to faster payments and, most importantly, allowing users to make micro-payments (which are common in P2P energy trading) for virtually zero overhead costs since there will be no intermediaries to handle the transactions. Despite P2P energy trading is the most common application of blockchain in the energy sector, other use cases are being explored, among them green energy supply certification [11], services for providing grid stability through energy redispatch [10], and fairness-control within microgrids [5].

3. System Design and Implementation

The main goal of this project is to develop and test a more efficient, blockchain-based backend system for the existing Power Share app and, more in general, improving the overall system performance especially in terms of energy consumption and transaction speed.

The first step was thus identifying the technology to be used instead of IOTA and a blockchain enabled smart contract technology seemed a good option. The main advantages of this solution is that smart contracts could be used to handle transactions and assets with much more efficiency and allow almost real-time payments between participants in the network, thus increasing the overall system performance and stability.

Ethereum was the first blockchain allowing to run smart contracts. Nonetheless, further blockchains - with different consensus algorithms and features offering the same opportunity of running smart contracts have been developed and thus were taken into consideration.

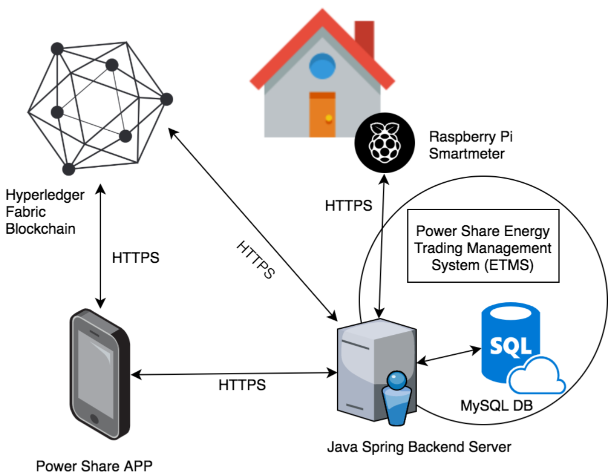

Figure 2: Power Share system architecture

However, after some tests with Hyperledger Fabric v1.2 and some written javascript chaincode (Hyperledger smart contracts), this option appeared to be the most suitable one (figure 2). The main factors leading to such choice were 1) the good documentation available, 2) the fact that it is open-source and 3) smart contracts can be written in Java, Javascript and Go. Hyperledger doesn't have its own cryptocurrency, however, the necessary assets (energy tokens, energy value and fiat currency) could be easily tracked and managed on this platform.

3.1. Hyperledger Fabric Blockchain Server

The PowerShare Blockchain Server is a prototype of a Decentralized Energy network where it mainly consists of a city-level community where Residents (small energy producers and energy consumers), Electric Vehicles (EVs), and different Utility companies (like the Empresa de Eletricidade da Madeira) can exchange energy between each other. Participants in the network need to have two virtual wallets, one for Cash (EUR) and one for Coins (a digital currency used as a mean of exchange for energy). Thus, in order to participate in the energy trading, participants must first exchange Cash for Coins. The network includes 4 typologies of participants (Residents, Electric Vehicles, Utility Companies and Banks):

- Residents: energy producers and energy consumers. Residents can own three assets: Energy, Coins and Cash. They can trade with fellow residents (buy or sell Energy), EVs (buy or sell Energy, transfer Coins to/from the EVs), banks (exchange Cash for Coins and vice versa), and utility companies (buy or sell Energy).
- Electric Vehicles (EVs) can own two assets: Energy and Coins. EVs can trade with other EVs (buy or sell Energy), Residents (buy or sell Energy and receive or send Coins the Residents), and utility companies (buy or sell Energy).
- Utility Companies (UCs) can own two assets: Energy and Coins. UCs can trade with Residents (buy or sell Energy) and EVs (buy or sell Energy).
- Banks can own two assets: Cash and Coins. Banks can trade with Residents (trade Coins for Cash or trade Cashs for Coins).

Also, the blockchain system has 3 different assets (Cash, Coins and Energy):

- Cash: Represents the Fiat money that a participant has in it's account. The cash asset is not tied to any currency, so a user could have euros, dollars or any kind of currency as it's cash asset. Cash asset is used in the CashToCoins, CashWithdrawalResident and CashFundingResident transactions;
- Coins: Represents the tokens that will be used to trade energy an used in the EnergyToCoins transaction. Coins asset is also used on the TransferCoinsToEV;
- Energy: Represents energy that is available to sell. Energy asset is used on the EnergyToCoins transaction.

In the blockchain system we have five different typologies of transaction:

- EnergyToCoins: This transaction represents the exchange of energy for coins between two blockchain participants. It could be performed by Residents, EVs and Utility Companies. Once the system receives the information regarding energy rate (in Coins/kWh) and energy value (in kWh), it performs the transaction by increasing the coin asset balance of the seller while decreasing his energy balance accordingly. The coin and energy assets of the buyer are updated too;
- CashToCoins: This transaction is responsible for the exchange of coins for cash between two blockchain participants. It could be performed by Residents and Banks, where Residents could get or sell coins to the Bank. At this moment, we are using euros as the main currency, but the system has the possibility to be extended to other fiat currencies. Once the system receives data about rate (Coins/EUR) and cash value (in EUR), the transaction is performed i.e. on the buyer side, the coin asset increases while the cash one decreases accordingly. On the seller side, the coin asset balance decreases while the cash balance increases;
- TransferCoinsToEV: This transaction is responsible of the coin transfer between a Resident and a EV. Residents could fund or withdraw coins from the coin wallet of an EV. Once the coin value to be transferred is defined, the transaction take place resulting in the decrease of the sender coin balance and a consequent increase of the receiver's coin balance;
- CashFundingResident: This transaction connects fiat currencies with the blockchain cash asset. Every time a Resident requests to fund his account, the blockchain administrator will initiate the CashFundingResident transaction, through which the Resident's cash balance is increased accordingly to the amount of fiat currency units provided to the blockchain administrator;

- CashWithdrawalResident: This transaction is similar to the CashFundingResident one, but it works the other way around. In this case, the Resident can request the blockchain administrator to withdraw money from his account and receive the corresponding amount of fiat currency in return while the system updates his coin balance accordingly.

3.2. Blockchain Admin Interface

The admin platform, Smile Hyperledger Interface, was developed as a tool for the administrator of the company operating the energy trading network. It can be used to manage Participants (Residents, EVs, Utility Companies, and Banks), verify assets and transactions within the network, as well as manually perform transactions between Participants. Residents could also request the administrator to fund or withdraw funds (cash) from their account.

3.3. Power Share Version 2 Android App

Before releasing the new version of the Power Share system, changes on both the ETMS java server and android app were made. Some tweaks to the ETMS system were made to remove the IOTA technology that was implemented on the old version of the system and replace it so as to connect the system to the new Hyperledger Blockchain Server.

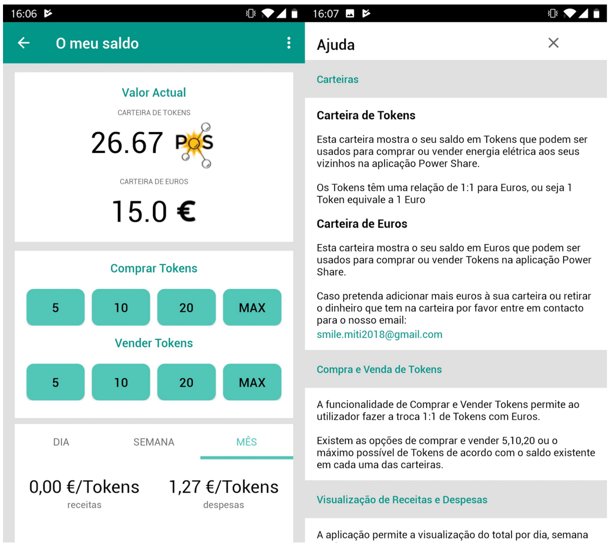

Figure 3: Power Share blockchain wallet

Instead of using IOTA addresses and generating new energy transactions associated with the IOTA accounts, transactions are sent to the Hyperledger Blockchain API and payments and assets are updated automatically. The wallet feature (figure 3) shows two virtual wallets that correspond to the user's assets on the Hyperledger blockchain server, one for Coins and the other for Cash (EUR).

The overall app performance and stability was improved and payments are fully automated with this new blockchain system and there is no need to generate payment addresses or manually request to make payments.

4. Results

Different methodologies have been used to test the system, adopting both quantitative and qualitative approach. Three are the components of the system that have been tested:

- The Hyperledger SMILE Admin Interface: in order to assess the user interface usability and collect some general feedback to improve it, we opted for adopting a qualitative approach - i.e. we performed a usability test (consisting of six tasks) using the think-aloud method;
- The new version of the Android application: in order to assess application performance and usage patterns, we electronically monitored the system and the interactions with it throughout the study by using the Fabric.io framework;
- The system backend: a quantitative approach was used to evaluate the system backend as well - i.e. data concerning its performance and energy consumption were collected and compared to those collected during the deployment of the previous system.

4.1. Qualitative assessment: the Blockchain Admin Interface

In order to assess usability and collect feedback on the Administrator Interface a small user test involving 5 participants (males, age ranging from 26 to 35 years, with a background in computer science and informatics) recruited among researchers at the Interactive Technologies Institute of Madeira was conducted. The test aimed mainly at assessing perceived usability, ease of use and clarity of the system, and was structured in two main blocks.

Feedback was collected using the think-aloud method. Some few general questions regarding positive/negative aspects of the system, perceived usability and ease of use, and structure of the platform have been asked. With explicit permission of the participants, the test was audio-recorded. For the purpose of this test, i.e. in order not to affect the system deployment, a new remote VPS Linux server was created with similar characteristics as the production server.

All participants in the user test of the Blockchain Admin Interface had no problems performing tasks 1 (read the platform description), 3 (check participant status) and 5 (manual transaction: sell energy). Two participants couldn't complete task 4 (add a participant) and one failed in performing task 6 (withdraw cash), while four out of five encountered some minor difficulties with task 2 (check the last transaction in the network) but only due the menu items labelling. The failure in task 4 was a system failure – i.e. the participant did perform the task correctly.

Except for a single system failure, the overall performance of the system resulted to be quite good. All participants reported to find the Admin UI clear and, when asked, they all say they would be able to use and explain it to someone else: "*I'd [be able to use and explain the system to someone else], despite this was the first time I've interacted with it. It might need to be slightly improved but definitely yes*" (Participant 1). All improvements suggested relates to the need of rewording some items - "*This 'Energy Value' is...one may think it is the production capacity, not the amount of energy he has. Should be something like 'energy available' or ' stored energy'*"' (Participant 4) - and adding search tool like filters and sort options - "*there might be some tool to search for a given participant and/or sort the columns*" (Participant 3).
They also appreciated the EVs feature - "*EVs...ohhh...so the EVs are another part of the system...like Vehicle to Grid...that's cool!*" (Participant 4) - as well as the overall structure of the system and the logic behind it "*In general, it is clear. I mean, I've understood what it is about. Categories are clear...very clear*" (Participant 2).
Results from this test provided several valuable suggestions on how to significantly improve the system usability by rewording some items and making minor changes to the UI layout.

4.2. Quantitative assessment: end-user app and system backend

To test the other system components - i.e. mobile app and system back-end - a small pilot was set up in Funchal (Madeira) involving the same sample that participated in the deployment of the preivous system. Due to these technical issues, only 6 households were included in the deployment to ensure reliability of the results and the test deployment lasted 3 weeks - from 7th to 28th of October 2019. Energy data was collected from the blockchain server and the ETMS server. Data regarding the interaction with the system and its performance was monitored and collected through the Fabric.io framework.

During the 3 weeks deployment, we counted 303 users' sessions. For what concerns their distribution, there was a peak in the first days after releasing the app, then the novelty effect passed and users' interest in the application decreased (figure 4 and 5). This result was expected, since users were already familiar with the application and no major changes were made on the UI except for the Hyperledger blockchain wallet. The same pattern was observed in the previous study.

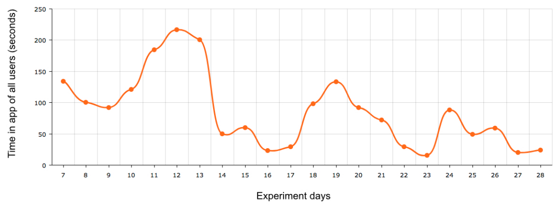

Figure 4: Android app time in during the experiment

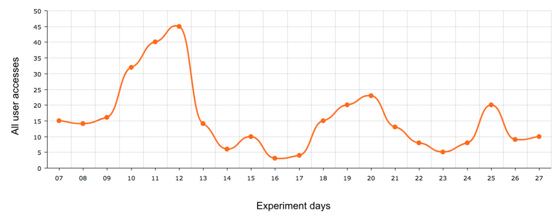

Figure 5: Android app accesses throughout the experiment

During the deployment - that involved 6 participants - a total of 207 energy transactions (table 1) were saved into both the ETMS server and the Hyperledger blockchain server, resulting in an average of almost 10 transactions per day. The transactions were generated by the ETMS that was built for the first version of the Power Share [4].

Table 1: Transactions data (grouped by day) during the three week study

	Transactions	**Eur**	**kWh**
Min	3	0,004	0.023
Max	17	0,499	3.067
Average	9.9	0,216	1,331
Total	207	4,554	27.959

At the end of the experiment, the 207 energy transactions resulted in a total of 27.959 kWh exchanged within the community. Compared to the previous study, both the daily average transactions (10 vs 19) and the amount of energy exchanged (27.9kWh vs 45kWh) are lower. Nonetheless, it must be taken into account that in the deployment of the new version we had one third less participants (6 out of 9). In addition, a further aspect that could have influenced the result is the weather. Indeed, the previous study was conducted in September, while our deployment occurred in October and, during the three weeks from 7th to 28th of October 2019, we had several cloudy days.

In terms of energy efficiency, and comparing two modern CPU's with similar characteristics a two core CPU (deployed on the new version of the system) consumes 40% less energy than the six core CPU (deployed on the last version of the Power Share System). In practice, this means that the first CPU has a daily energy consumption 0.648kWh and a yearly consumption of 236.52kWh, while the more powerful CPU has a 1.08kWh of daily energy consumption and a yearly energy consumption of 394.2kWh. In conclusion, after the comparison between the two similar processors, we can assume that the new blockchain implementation of the new blockchain server is more efficient and consumes less energy than to the IOTA node used in the previous implementation.

5. Conclusions

A new version of the Power Share system, composed of the android app, ETMS and Hyperledger blockchain server, was successfully implemented and tested in a small pilot study run in Madeira from 7 to 28 October 2019. The IOTA cryptocurrency was replaced by a new smart contract blockchain system based on Hyperledger Fabric, bringing a more stable, energy-efficient system to perform energy transactions between residents. Also, the java app backend and the android app interface were upgraded to this new version, and the code was revised to improve overall stability and performance. Most of the current blockchain systems have high energy consumption for verification and validation of data [9]. To overcome this issue, the new Power Share system uses a permissioned blockchain system with a more efficient consensus algorithm, which results in lower energy consumption.

At the end of the development, we have tested and evaluated our system by adopting both quantitative and qualitative approaches. This, in order to understand if it was clear and easy to use for both the Admin and end-users, as well as to assess its performance. Concerning users engagement with the Android application, which underwent minor changes, the results we obtained are similar to those from the previous study. On the contrary, we found evidence that the system efficiency, performance and automation of processes with blockchain service are significantly improved.

5.1. System Limitations

The current Power Share implementation consists of a small scale P2P energy trading community - i.e. 6 prosumers simulating a small microgrid. To assess the system scalability, a larger sample is needed. In addition, it should be pointed out that, since both the REST API endpoint and the web application - admin blockchain interface - are implemented on a single server, with all the blockchain components distributed on docker containers, the blockchain network as it is now is susceptible to DDOS attacks - i.e.the service could be stopped causing transactions requests to be rejected by the blockchain service. A further weak point of the system relates to the reliability of the data coming from the smart meters. With the current setting, a user can easily cheat the system simply by switching the production and consumption cables. This way, instead of buying energy, they could act as energy sellers and crediting them as energy producers. Since the monitoring system installed in the households of the participants in the study is part of the SMILE project demonstrator we could not act upon it. Nonetheless, it should be pointed out that, in a real-life scenario, tamper-proof seals should be implemented on the smart meters in order to ensure reliability of the data. The end-user application, which is needed to join the energy community, has been developed only for Android based devices. This is a further limitation. To foster adoption of the system, a version of the application compatible with other OS platforms should be developed.

5.2. Scalability

The Hyperledger blockchain system we deployed consisted of only one blockchain peer, all the necessary Certificate Authorities and blockchain orderer were in docker containers. However, the system could be easily extended and used as a testbed to simulate a bigger scale energy transactive grid. The rationale behind the system is to allow for transactions between small microgrids (preventing hop and high transmission costs) but also to give Residents the opportunity to choose their energy supplier among all peers (figure 6).

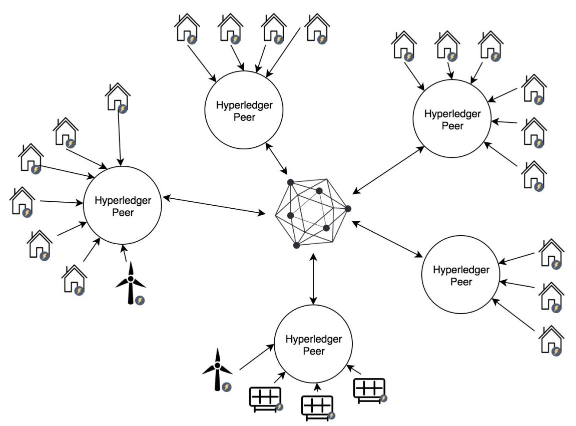

Figure 6: Representation of the Powershare system replicated to the Electrical Grid

The node peers would be those participating in the Hyperledger blockchain consensus and all the transactions on the grid would be recorded on the nodes and publicly available. This way, the system could be scaled up to cover the whole Madeira island, where these microgrids could be deployed by installing Hyperledger peers on small residents gathering, which would be then connected to the Hyperledger network. With the necessary adaptations, it could also be deployed to other locations and scales.

5.3. Future Work

The Power Share blockchain server was developed based on new technologies but there are still rooms for improvement from multiple points of view. The REST API and blockchain service were developed on Hyperledger Fabric v1.2, however, by the time of this writing, Hyperledger released version v1.4 which features significant improvements to the developer experience. The smart contract structure, Hyperledger network model and blockchain code could be updated to run on the newer Hyperledger versions. The energy matching algorithm, that is currently running on the ETMS java server, could also be improved and moved to the blockchain system with the use of a smart contract energy bidding structure, thus further increasing the system automation. A further improvement relates to the algorithm itself, which so far does not take into account the losses that occur when the energy is injected into the grid and hop energy loss and cost to the destination. Finally, the Android app could be upgraded by adding further network participants, specifically EVs and Utility Companies. In order to compare results from the deployment of the previous system version and the new version, we decided to keep the same features of the previous version of the application. Nonetheless, by allowing end-user to interact and trade with further participants, we can provide them with further control over their energy suppliers and the source of the energy they are using, thus ultimately fostering the consumption of carbon free energy.

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References

[1] C. Cachin and M. Vukolicvukolic. Blockchain Consensus Protocols in the Wild. Technical report, 2017.

[2] M. Castro and B. Liskov. Practical Byzantine Fault Tolerance. Technical report, 1999.

[3] E. Commission et al. Study on residential prosumers in the european energy union, 2017.

[4] T. Correia. *Power Share: Eco Feedback and Energy Trading System.* MSc dissertation, Universidade de Lisboa - Instituto Superior Técnico, Lisbon, 2018.

[5] P. Danzi, M. Angjelichinoski, Č. Stefanović, and P. Popovski. Distributed proportional-fairness control in microgrids via blockchain smart contracts. In *2017 IEEE International Conference on Smart Grid Communications (SmartGridComm)*, pages 45–51. IEEE, may 2017.

[6] S. De Angelis, L. Aniello, R. Baldoni, F. Lombardi, A. Margheri, and V. Sassone. Pbft vs proof-of-authority: applying the cap theorem to permissioned blockchain. 2018.

[7] J. Froehlich, L. Findlater, and J. Landay. *The Design of Eco-Feedback Technology.* 2010.

[8] J. A. Garay, A. Kiayias, and N. Leonardos. The Bitcoin Backbone Protocol: Analysis and Applications *. Technical report, 2019.

[9] P. Global. Blockchain-an Opportunity for Energy Producers and Consumers? *PwC global power & utilities*, pages 1–45, 2017.

[10] Hörchens and Ulrike. Europe's first blockchain project to stabilize the power grid launches: TenneT and sonnen expect results in 2018. Technical report, 2018.

[11] F. Imbault, M. Swiatek, R. de Beaufort, and R. Plana. The green blockchain: Managing decentralized energy production and consumption. In *2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, pages 1–5. IEEE, jun 2017.

[12] S. King and S. Nadal. PPCoin: Peer-to-Peer Crypto-Currency with Proof-of-Stake. Technical report, 2012.

[13] L. Lamport, R. Shostak, and M. Pease. The byzantine generals problem. *ACM Transactions on Programming Languages and Systems (TOPLAS)*, 4(3):382–401, 1982.

[14] S. Nakamoto. Bitcoin: A peer-to-peer electronic cash system. 2008.

[15] V. H. Nguyen, Y. Besanger, Q. T. Tran, and M. T. Le. On the applicability of distributed ledger architectures to peer-to-peer energy trading framework. *arXiv preprint arXiv:1810.05541*, 2018.

[16] S. Popov. IOTA whitepaper v1.4.3. pages 1–28, 2018.

[17] J. Schlund, L. Ammon, and R. German. Ethome: Open-source blockchain based energy community controller. In *Proceedings of the Ninth International Conference on Future Energy Systems*, number June, pages 319–323. ACM, 2018.

[18] M. Vukolicvukolic. Rethinking Permissioned Blockchains.

[19] M. Vukolicvukolic. The Quest for Scalable Blockchain Fabric: Proof-of-Work vs. BFT Replication. Technical report.