Problem Description

In a limited electrical system (a microgrid, such as an island community) there will be some, one or more, energy producers (e.g. diesel generators), some consumers and some, zero or more, prosumers (consumers who also produce energy, e.g. by solar panel or wind turbines). In addition, there may be energy storage such as batteries.

The prosumer may at times produce more energy than they themselves use at the moment and sell this surplus energy to a neighbor who needs it. In an advanced solution, one can imagine that the prosumers have a separate battery that they can choose to charge instead of selling the energy. There are three sources of energy for the consumer in the described limited energy system; the pure manufacturers (e.g. diesel engines), the batteries (which sometimes buy energy) and the prosumers.

In the system, there are also consumers, who buy energy. The price of delivered energy may vary from source to source and over time. An optimization of energy based on different criteria may be interesting, but this will not be considered. In order to settle the value of the energy flowing in the system, one wants to look at the use of blockchain technology.

The task will be:

- Look at how blockchain technology is used and can be used in microgrids.
- Suggest a blockchain-like system that can calculate the value of the energy flowing. This system may have a user interface where offer and demand are displayed.
- Implement the proposed system and test it using simulated data.

Preface

This paper is submitted on partial fulfillment of the requirements for the Master of Science degree at the Norwegian University of Science and Technology (NTNU).

The problem description for this thesis was given by supervisor Geir Mathisen, who has also provided helpful guidance in the system development, especially with regard to understanding the problem description and development of functional specifications.

The system was implemented and tested on a standard PC, using Python. Several Python libraries were used in the implementation. These were *Twisted, Flask, ECDSA, and datetime*, as well as the Python standard libraries *os, csv, hashlib, uuid, random, pickle, json, time, and struct.* The implementation of the consensus model and the blockchain are based on findings from the background chapter.

Abstract

Sammendrag

Abbreviations

RPC	=	Remote Procedure Call
EVM	=	Ethereum Virtual Machine
API	=	Application Programming Interface
BFT	=	Byzantine Fault-Tolerance
BGP	=	Byzantine Generals Problem
PoW	=	Proof of Work
PoS	=	Proof of Stake
ASIC	=	Application Specific Integrated Circuits
PBFT	=	Practical Byzantine Fault Tolerance
PoC	=	Proof of Concept
P2P	=	Peer-to-Peer
NOK	=	Norwegian Kroner
UUID	=	Universally Unique Identifier

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Chapter 1

Introduction

1.1 Background and Motivation

In 2008, after years of granting loans to "sub-prime" clients who struggled to repay their mortgage, the investment bank, Lehman Brothers, filed for bankruptcy [1]. The events that followed launched a global financial crisis with the stock market dropping and unemployment rate increasing world wide. The banks who initially caused the crises, however, were bailed out, using tax payer money. People no longer felt they could trust bankers or investment managers. As a response to this, Satoshi Nakamoto outlined a trustless peer-to-peer (P2P) electronic cash system in the Bitcoin whitepaper.

When the bitcoin system became a reality in the start of 2009, the very first block contained the message "The Times 03/Jan/2009 Chancellor on brink of second bailout for banks". Furthermore, Nakamoto posted the following on an internet P2P forum [2] in 2009:

"*The root problem with conventional currency is all the trust that's required to make it work. The central bank must be trusted not to debase the currency, but the history of fiat currencies*[1] *is full of breaches of that trust. Banks must be trusted to hold our money and transfer it electronically, but they lend it out in waves of credit bubbles with barely a fraction in reserve. We have to trust them with our privacy, trust them not to let identity thieves drain our accounts. Their massive overhead costs make micropayments impossible.*"

The distributed system was backed by mathematics and cryptography, instead of traditional trusted middlemen and third-parties. The Bitcoin technology removed

[1] Fiat currency is currency backed and issued by the government, such as U.S. dollars or Norwegian kroner

the need for trust in transactions, due to the distributed, decentralized ledger where all transactions are stored. Since all transactions are stored across all nodes in the network, there is no single point of failure. Unlike traditional databases, this distributed system cannot be hacked, and once data is stored in the ledger, it cannot be altered.

Cryptocurrencies were not invented by Nakamoto, they existed already in the 1980's, but never saw any real usages as they had some problems. What set Bitcoin aside, was the solution to the *double spend problem*[2]. Nakamoto solved this by timestamping all transactions and storing them in a immutable, decentralized ledger - the blockchain.

Bitcoin and *cryptocurrency* have become household words, with nearly daily appearances in media. Although many people still use the terms *Bitcoin* and *blockchain* interchangeably, they are not the same. Bitcoin is, simply put, the first application created using blockchain technology. Parallels can be drawn to the early days of the Internet, where TCP/IP (Transmission Control Protocol/Internet Protocol) became the technology that allowed e-mail to become a reality [3], just like the blockchain technology enables Bitcoin.

Since the introduction of blockchains, there has been massive development in the field with the creation of many new applications, both financial and non-financial. With usage ranging from bank-to-bank transfer, to voting, recording landownership, and sale and licensing of intellectual properties, blockchains could impact many industries.

Among the industries who have adopted the blockchain as a method to improve transactions, is the electricity market. In 2014, a method to trade renewable energy through virtual currency was proposed with the NRGcoin [4]. The first successful energy transaction to be executed in a blockchain occurred with the Brooklyn Microgrid project in 2016 [5]. In spite of being a relatively new technology, blockchains in the electricity market have shown great potential. Especially in a P2P system, such as microgrids, is a promising area for blockchains. Since there is no central utility that distributes the electricity, there does not need to be a central authority controlling settlements in the system.

1.2 Limitations

In a complete system for settling transactions in an electricity system, there are several aspects that ought to be considered. Among these are privacy, however, the system implementation in this thesis is focused around the technical design and implementation. Therefor, privacy is not part of the implementation, but will be further discussed in chapter 9. Another important aspect that should be considered in a complete system is the optimization of the settlement algorithm. This is a

[2]If person A has an asset and sends this to person B and C simultaneously, which transaction should be valid.

very complex task and is not part of the scope of this thesis. A well functioning user-interface is required in order for the proposed system to work. This task is only outlined in the design and implementation, as a full functional user-interface is deemed too time consuming to develop, and the main focus of the implementation is centered around the blockchain. The task of creating a fully functional smart contract API is also deemed as too complex a task to be implemented in the limited time of this thesis. However, this process is outlined in section 5.2.1 and further discussed in chapter 9

1.3 Contribution

Contributions in this thesis are summarized as:

1. Presentation of relevant background theory relating to the system.
2. Outline existing implementations of blockchains used in peer-to-peer electricity trading.
3. Propose a new blockchain-like system for storing electricity transactions.
4. Propose a simple method for settling electricity transactions in the system.

1.4 Thesis Outline

Chapter 2 presents a short description of microgrids and a theoretical background of blockchains, starting with an introduction to blockchains. Furthermore, taxonomy and mechanisms such as consensus are explained. Existing blockchain applications are also discussed. Related work on projects using blockchains in energy transactions are presented in chapter 3.

The functional specifications of the system to be implemented are presented in chapter 4. The system mainly consists of two parts: implementation of a blockchain for storing data in a distributed network; and an application for settlement of energy transactions in a microgird. The blockchain is the back-end service enabling the functionality of the application.

A system design is illustrated in chapter 5, while the implementation of the system is described in chapter 6. Testing and results are presented in chapter 7 and 8, respectively, while discussion and conclusion of the thesis will be presented in chapter 9 and 10, respectively.

Chapter 2

Background

This chapter mainly contains relevant background theory on blockchains. The chapter starts off with a very basic introduction to microgrids. Related work on the subject is presented at the end of the chapter.

2.1 Microgrids

A microgrid is a local power grid that may or may not be connected to the main grid. The microgrid can either work as an extension of the main power grid, or operate in "island mode" and function autonomously. A formal definition of a microgrid is as follows:

"*A Microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid*" [6].

Microgrids usually include renewable energy sources, such as wind generators, small hydro power generation, and photovoltaic solar panels, that are locally grouped together. Microgrids may also include generators and batteries to ensure reliability [7]. By placing power generation and power usage closer together, efficiency will be increased and transmission losses reduced [8].

A key benefit of the microgrid, is the ability of being self-sufficient in case of emergencies that cause blackouts. By disconnecting from the grid, the locale area powered by the microgrid can operate for days without any connection to the main grid. This happened, for instance, in New York during hurricane Sandy in 2012 [9]. The city was without power for several days, but hospitals and other key facilities could operate due to microgrids.

Places that are not connected to the main grid have very expensive solutions for getting power. This can typically be rural places or islands. They may also benefit from microgrids. The ability to operate in island-mode will provide better electricity services at a lower cost than e.g. importing diesel [10].

2.1.1 Electrical Transmission

In microgrids, just like in the traditional power grid, there is no way of telling where consumed electrons are actually generated. Once a power plant or another power producer put electricity in to the grid, the electrons from all sources are mixed together before they are transferred to consumers [11]. The electricity sources are indistinguishable. In a microgrid, this means that even if producer A has a contract with consumer B to deliver electricity, consumer B is not necessarily using the electrons that producer B has generated. If producer C is also generating electricity to the gird, there is a chance that consumer B is actually consuming the electrons from producer C. Electrons in the grid always flow from source (generators) to sink (loads), where electricity is being consumed [12].

2.2 Introduction to Blockchain

A blockchain is a decentralized ledger, distributed over a network of nodes. Transactions in the network are stored in blocks which are linked together as a chain, creating the blockchain. It was first introduced by Satoshi Nakamoto with the Bitcoin application [13].

The blockchain is primarily used to transfer assets between users. In contrast to previous transaction methods, there is no need for trust between the participants of the transaction, nor the need of a trusted third-party institution, like a bank or government. The trust lies in the system, and the mathematical functions behind it, and not the individual participants [14]. Due to the decentralization of the network, there is no single-point-of-failure, as the database is duplicated on every node of the network.

The following description of the blockchain technology is based on the Bitcoin blockchain proposed in Nakamotos whitepaper from 2008[13]. Many of the features from the Bitcoin blockchain hold true for most blockchains. However, there are many variations of blockchain implementations, due to public/private configurations, consensus models etc. These differences will be described later in the chapter.

When a node transfers an asset to another node, it creates a transaction. The transaction contains: one or more inputs; one or more outputs; and a digital signature. In Bitcoin, an input is a previously received and unspent output, containing the amount of bitcoins. Multiple inputs can be added together to create a larger transaction. The inputs are used completely, so if the amount does not add up to the wanted output, multiple outputs can be used so that the change is sent back to the owner. This is because transactions must reference an output, and each output can only be referenced once. Thus, the exact ownership of every asset can be pinpointed to a user in the network, based on the previous transactions. In order for a transaction to occur, it must be proved that the asset has not been previously spent by the current owner. Thus, there is no way to double spend assets.

Transactions are validated through digital signatures, proving the authenticity of a message, by using public and private keys. Each node can obtain a random private key, and a corresponding public key derived from the private key. If node A wants to send a Bitcoin to node B, it must use B's public key, which acts as the address to B's Bitcoin wallet. Node A creates a digital signature of the transaction with its private key. The validity of the transaction can then be confirmed using A's public key. When the transaction is confirmed, the Bitcoin can only be spent by the person in possession of the private key corresponding to B's public key. This transaction is illustrated in figure 2.1. The use of digital signatures ensures that transactions can traverse the network without being altered, as even the smallest change will cause a signature to no longer be valid.

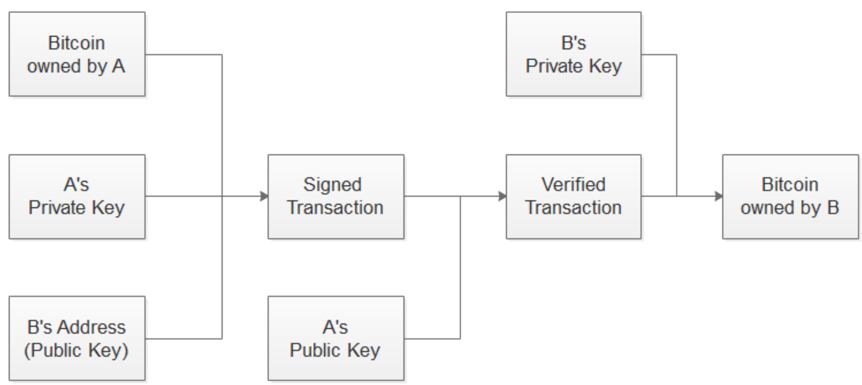


Figure 2.1: Digital signature in Bitcoin transaction.

A miner stores multiple pending and unconfirmed transaction together to create a block. The block consists of the transactions, as well as the block header. The block header usually contains: a reference to the previous block in the chain, namely the hash of the previous block; a timestamp for when the new block is created; and a nonce and a target used to calculate the hash of the new block.

When the hash of the new block is found, the block is broadcasted to the rest of the network. Every node on the network validates the block, before they start working on the next block. Validation is an easy task, once the hash is found. If several miners find the solution to the next block at the exact same time, a fork is created. This sequence is illustrated in figure 2.2

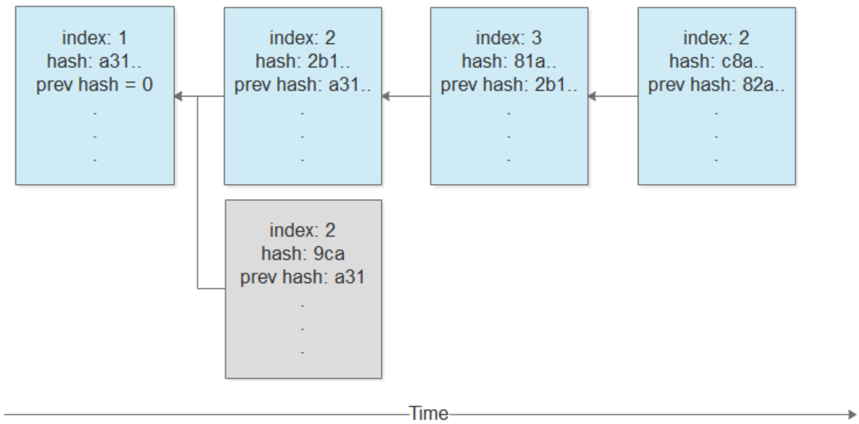


Figure 2.2: Connection between blocks.

A fork means that there exists two (or more) different versions of the blockchain in the network. Due to network latencies, nodes in the network will receive different broadcasted messages at different times. Therefore, nodes might have different versions of the blockchain. The miners start working on the next block based on the one they received first, while storing the other version in case that fork becomes longer [13]. The fork is resolved when one side of the fork becomes longer than the other(s), which will most likely happen when the next block is created. The side with the longest chain always wins because it is backed by the most work. All the nodes in the network immediately look to the longest chain as the valid version of the blockchain. The transactions in the discarded block go back into the pool of the pending transactions, waiting to be mined in a block. Once a transaction is part of the blockchain, it is irreversible. Due to the hash functions, even the slightest alteration in a transaction will be detected, and the transaction will be deemed as non-valid. Thus, a transaction cannot be changed or reverted once it is part of the blockchain. There is however some need for caution. As previously mentioned, transactions in discarded blocks go back to being unconfirmed. If the other side of the fork contains a transaction attempting to double spend the asset, the initial transaction might no longer be valid.

Say, for instance node A sends two bitcoins to node B, while also sending the same two bitcoins to itself, only one of these transactions can be valid. Once a transaction is stored in the blockchain, the two bitcoins are referenced as a new unspent output, and the other transaction is no longer valid. This is intentional behavior in the blockchain, as it solves the problem of double spending which is usually what a trusted third-party, e.g. a bank, is needed for. The problem occurs when there is a fork. If node B receives the bitcoins as a payment for some goods, and ships the goods once the transaction is part of the blockchain, while node A is simultaneously working on another fork in the blockchain containing the transaction sending the two bitcoins to itself, node B will lose the payment for the goods if the fork node A is working on becomes longer. It is therefore a good policy to wait until the block containing the transactions has multiple successors before asserting the transaction final.

2.3 Blockchain Taxonomy

This section details the taxonomy of blockchains, in particular how they are governed and the level of authorization needed in the different classifications. Blockchains are usually divided into three different categories, depending on the way they are governed [15, 16, 17].

- Public blockchains, like Bitcoin, is a blockchain where anyone is free to participate, and is completely decentralized.
- Private blockchains are more centralized with e.g. a single organization controlling the blockchain.
- A consortium blockchain is a hybrid between the two, where participants must be authorized, but there is no single, central authority controlling it. It is also described as "*[...] a traditional centralized system with a degree of cryptographic auditability attached*"[15].

Authorization in the blockchain depends on whether they are permissioned or permissionless. Permissionless blockchains are open to anyone, while permissioned blockchains require approval from the owner or members to join. Public blockchains are categorized as permissionless, while private and consortium blockchains fall under the category of permissioned.

The characteristics of public, private and consortium blockchains are summarized in table 2.1.

In conclusion, the type of blockchain most beneficial for each application will vary from industry to industry and from application to application. Public blockchains are most beneficial for individual users, as there is no need for trusted third-parties or trust between users. Private and consortium blockchains are more beneficial to organizations or companies, as they lower cost and increase speed of transactions.

Table 2.1: Comparison between public, private, and consortium blockchains.

	Public	Private	Consortium
Consensus	All miners	One organization	Some nodes
Authorization	Permissionless	Permissioned	Permissioned
Performance	Slow	Very fast	Fast
Security	Nearly impossible to alter	Could be altered	Could be altered
Centralization	No	Yes	Partially
Computational expensiveness	Costly	Cheap	Depends on consensus
Area of use	Crypto-currency	One organization	Several organization with some trust
Anonymity	Yes	No	No

2.4 Consensus Models

Consensus models are important in distributed systems, in order to reach distributed agreement and maintain a correct and concise version of the shared ledger between the nodes [18]. There are two different types of fault-tolerance in consensus mechanisms. Fail-stop fault-tolerance means that the system is able to perform correct behavior if it is able to detect nodes that have failed. Byzantine fault-tolerance (BFT) means that the system performs correct behavior even if there are malicious nodes that intentionally try to cause failures in the system. BFT protocols are designed to be a solution to the Byzantine Generals problem (BGP) [19]. Roughly explained, the BGP is a compliance problem where generals in the Byzantine army must agree upon whether to attack or retreat, using only messages, even if there is a traitor among them.

2.4.1 Proof of Work

Proof of Work (PoW) is the consensus model presented by Nakamoto in the Bitcoin white paper [13], and the most commonly used consensus protocol in blockchains CITE. In the PoW consensus model, nodes are required to put a certain amount of work into creating new blocks to avoid DDoS-attacks and to make it harder for malicious nodes to hijack the blockchain. The required work consists of solving a computationally expensive cryptographic problem. Each new block has a unique hash based. The problem consists of combining this hash with a variable called nonce, to find a hash that is less than a given target (e.g. a 256 bit hash containing x significant zeros). While the proof is somewhat difficult to find, it is very fast and easy to verify by the rest of the network.

By lowering the target value, the problem can be adjusted to be more difficult. The amount of work required is exponential to the number of significant zero bits. This implies that untrustworthy peers wanting to modify past blocks have to work much harder than peers adding new blocks, due to the work required to redo already mined blocks. This can be seen in figure 2.3

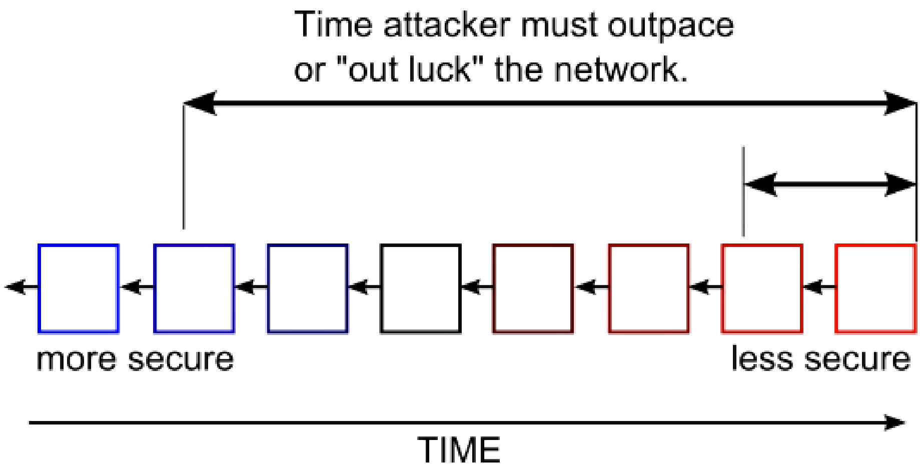


Figure 2.3: Transactions in blocks are in less danger of being altered as more time passes [20]

Nodes working on fining these proofs are called miners, and receive some form of rewards for finding the correct proofs (e.g. a certain amount of the cryptocurrency or transaction fees). Special Application Specific Integrated Circuits (ASIC) computers are created for mining. These computers solve the hash problems at higher rates and with less energy consumption than normal computers [21]. By letting anyone participate as a miner it is ensured that the network has complete decentralization.

As described by Nakamoto, PoW is also a method for ensuring that a majority always controls the blockchain [13]: "*If the majority were based on one-IP-address-one-vote, it could be subverted by anyone able to allocate many IPs. Proof-of-work is essentially one-CPU-one-vote*". The longest chain reflects the most proof-of-work and, thus represented by the majority in the network.

Some of the major problems related to PoW come from the latency and vast amounts of energy required to mine new blocks. As of May 2018, the Bitcoin blockchain consumed more energy than the entire country of Switzerland [22], as seen in figure 2.4.

Nakamoto shows that the probability of an attacker altering a block decreases as more blocks are added on top of it [13]. However, the probability never reaches zero. An example of this is the 51 % attack, where a group wishing to attack the blockchain gains 51 % of the computation power, and thus is in control of the blockchain.

PoW ensures that the blockchain eventually reaches consensus. Due to the possi-

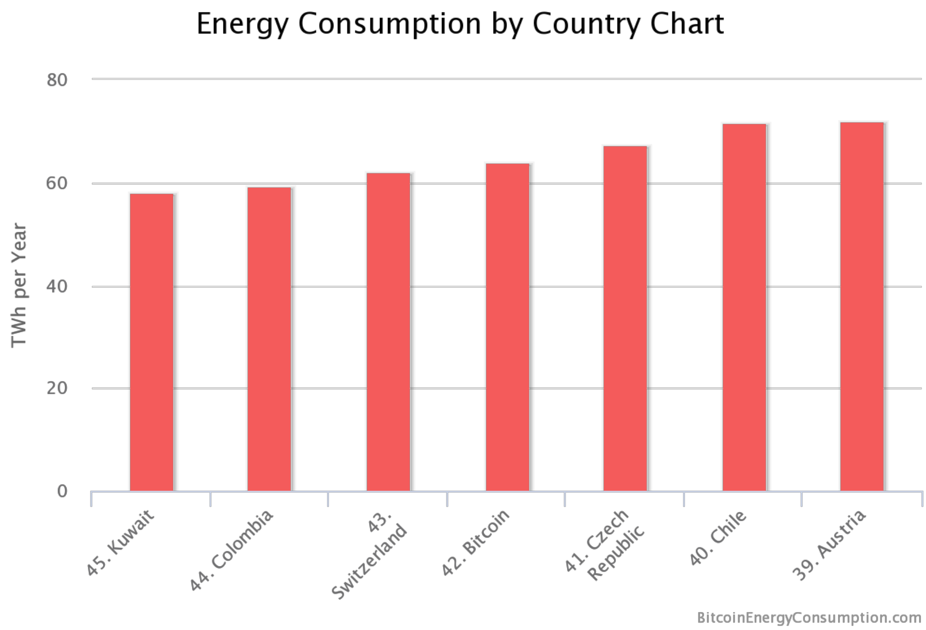


Figure 2.4: Bitcoins energy consumption index relative to countries in the world [22]

bilities of forks in the chain, it might take some time for the network to agree on the final version of the ledger. This results in slow transaction time with only 7 transactions per second, compared to VISAs throughput of 10 000 transactions per second [23].

2.4.2 Proof of Stake

Proof of Stake (PoS) was created to solve the energy problem of PoW [23, 17]. Nodes are chosen to participate in the consensus process in a deterministic manner, based on the amount of stake they have in the system. This means that if a node, or stakeholder has 10 times more assets in the network than another node, it is 10 times more likely [24] to be chosen to forge new blocks and hence receive a reward. The reward in PoS comes from transaction fees, as there are no new coins to be mined, or created, since all coins exists from the start of the blockchain.

The creator of a new block puts his or her own coins at stake. This means that if they produce a block containing fraudulent transactions, they lose their stake. After putting up the stake, the node becomes part of the validation process. Due to their stake in the block, they are incentivized to only validated the correct transactions. The problem occurs when a validator has very little, or nothing, at stake. It is more economical profitable to vote on multiple blocks, supporting multiple chains in order to maximize expected rewards [23, 18]. This problem is known as the nothing-at-stake problem. Ethereum, who is currently using PoW but plan to change to PoS in a future release, proposed a solution to the nothing-at-stake problem by penalizing validators who vote for the wrong block [24].

A major problem with this model is that the rich get richer, due to the selection process favoring nodes with more stake. This, in turn, implies that the network will be more centralized over time. However, it can be argued [25] that PoW favors the rich even more, as it is more expensive to purchase hardware required for mining and electricity costs, than buying coins in the blockchain to be more likely to participate in the validation process [26].

2.4.3 Raft

Raft is a partially asynchronous, leader based consensus algorithm for managing replicated logs across a distributed system [27]. Raft was designed to be a more understandable alternative to Paxos [28]. The algorithm was first proposed by Onargo et al [27]. Following is a description of the algorithm.

The Raft algorithm consists of three main parts: **leader election**, **log replication**, and **safety**. Any node participating in the consensus process is in one of three states: leader, follower, or candidate.

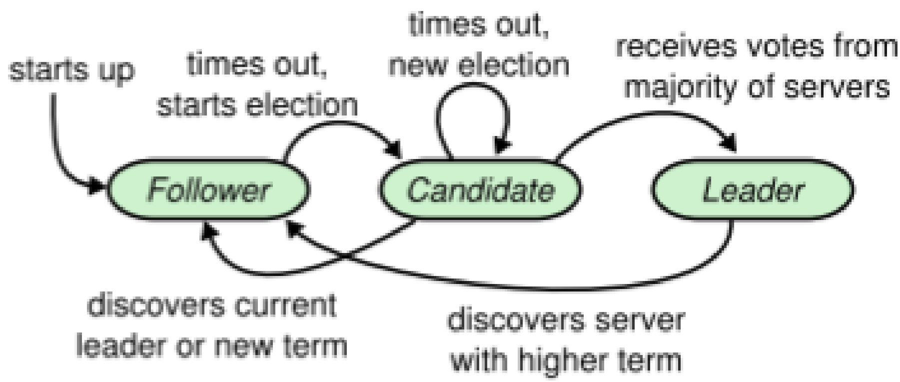


Figure 2.5: Server states. [27]

Time is divided into terms in Raft. Each term is of arbitrary length, depending on the operation of the leader. Each term starts with a **leader election**. If a node has not heard anything from a leader after a certain amount of time, it becomes a candidate and request votes from other nodes in the network. There are three possible outcomes for a candidate:

1. The candidate receives a majority of votes and becomes leader.

2. The candidate receives a message from another node claiming to be the leader. The candidate then steps down and becomes a follower.

3. If the candidate does not receive a majority, e.g. due to a split vote, it will start a new term and a new election.

The algorithm guarantees that the following properties are true at all times, thus ensuring consensus:

- "**Election Safety:** *at most one leader can be elected in a given term*"
- "**Leader Append-Only:** *a leader never overwrites or deletes entries in its log; it only appends new entries*"
- "**Log Matching:** *if two logs contain an entry with the same index and term, then the logs are identical in all entries up through the given index*"
- "**Leader Completeness:** *if a log entry is committed in a given term, then that entry will be present in the logs of the leaders for all higher-numbered terms*"
- "**State Machine Safety:** *if a server has applied a log entry at a given index to its state machine, no other server will ever apply a different log entry for the same index*"

When the system operates under normal conditions, there is exactly one server and all other nodes are followers. The followers are passive, and only respond to requests from leaders or candidates through Remote Procedure Calls (RPC). Each **log entry** consists of an index and a term, as well as some data. If two entries in different logs have the same index and term, all entries up to that point are guaranteed to be identical. Leader cannot overwrite any committed log entries, only append new entries.

Safety is ensured in Raft by putting restrictions on which nodes can become leaders. A candidate must include all previous committed entries in its log, in order to become a leader. The leader also ensures that any followers missing entries are brought up to date.

In Bitcoin, and other blockchains with PoW consensus, transactions are never finalized, in the sense that they can become part of a fork. As time passes and more blocks are created, a transaction is less likely to be part of a fork. In Raft however, transactions are finalized when the block becomes part of the blockchain. Due to the leader configuration and validation prior to the blockchain, forks do not occur.

Raft is not a BFT consensus protocol, it is only fail-stop fault-tolerant. All nodes participating in the consensus are assumed to be trusted, meaning that there are no Byzantine faulty nodes.

2.4.4 Practical Byzantine Fault Tolerance

A Byzantine fault-tolerant algorithm is one that can tolerate Byzantine faults that usually occur in network systems with multiple nodes communicating. These types of faults include:

- Messages lost due to network failures.
- Messages corrupted through malicious nodes.
- Messages compromised through man-in-the-middle. attacks.
- Hardware or software failures.
- Messages from nodes without permission to join the network.
- Arbitrary behavior.

The Byzantine Generals problem was first proposed and solved by Lamport et al. [19]. However, the solutions presented in the paper are expensive in regard to time and message overhead, thus making it impractical to use in real systems. A solution to this problem was proposed by Castro et.al [29] with their new *Practical Byzantine Fault Tolerance* (PBFT) algorithm.

The PBFT algorithm states that the system is able to make progress with f faulty nodes, if the total number of nodes n, is

$$n = 3f + 1$$

Out of the n nodes in the consensus model, one is the primary, which receives requests from the client, and the rest of the nodes are replicas. After receiving a request, the primary initiates a three-phase protocol, (pre-prepare, prepare, and commit) to ensure consensus. Results from all replicas are sent to the client, who in turn accepts the result if there are f+1 identical replies. In the pre-prepare phase, the request is given a unique sequence number, which the replicas agree on in the prepare phase. The commit phase establishes total order across views. The order of communication in the three-phase protocol can be seen in figure 2.6.

Hyperledger Fabric provides consensus as a modular component in the system, supporting various kinds of consensus models. One module utilizes PBFT to order transactions in the system, thus ensuring that all peers have the same list of transactions in their ledger [30, 31].

2.4.5 Summery of Consensus Models

This is perhaps the most challenging aspect in order to create a blockchain. Different types of blockchains require different types of consensus models. At this point, no single best consensus model exists. Limitations and restrictions are present in regard to power consumption, scaling, security and transaction speed. These challenges will be further discussed in the following section.

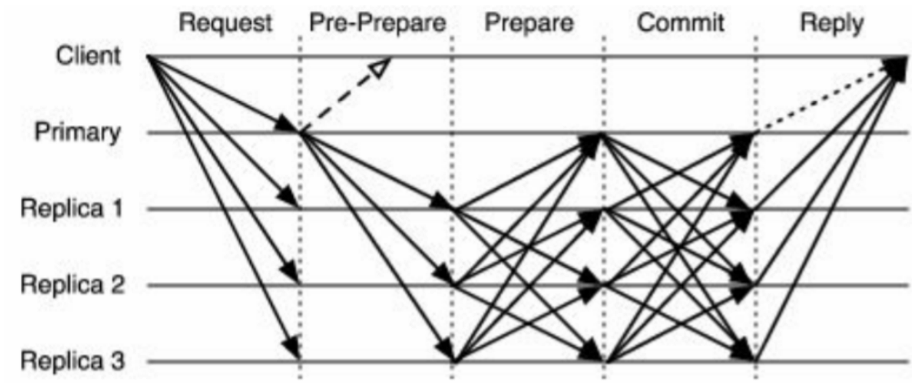


Figure 2.6: Three-phase protocol for consensus in PBFT [29].

Table 2.2: Consensus models

Protocol	PoW	PoS	Raft	PBFT
Requires crypto	Yes	Yes	No	No
Leader	No	No	Yes	Yes
Pros	Decentralized	Energy efficient		High throughput Low cost
Cons	Slow throughput Energy inefficient	Nothing at stake	Not BFT	Semi-trusted
Implementations	Bitcoin Ethereum	Peercoin Ethereum		Hyperledger Tendermint

2.5 Blockchains and Their Applications

Numerous blockchains have been created since the Bitcoin blockchain was published. Many blockchains, like Bitcoin, are based around crypto-currency. However, there are several blockchain with other purposes than being purely a crypto-currency, such as the Ethereum blockchain. Some of these blockchains will be discussed in this section.

2.5.1 Bitcoin

How Bitcoin works, was roughly described in section 2.2. This section will discuss what Bitcoin is used for and in what applications it is beneficial for. Bitcoin is first and foremost a crypto-currency blockchain, so the applications are financial.

The Silk Road drug market [32], albeit illegal, is perhaps the field where Bitcoin provided the most convenience for its users, before it was shut down by the FBI in 2013. By using Bitcoins as payment, the marketplace ensured anonymous drug trading. In its 2.5 years of operation, the dark web market had sales worth over $ 1 billion [33].

Another major advantage of Bitcoin is transferring money abroad [34]. Compared to traditional transfers between banks which are both costly (on average 7.45% [35]) and might take up to several days, Bitcoin has no extra transaction fees and new transactions are processed in minutes or hours, depending on the network traffic [36].

An example of an application built on top of the Bitcoin blockchain is Lighthouse [37]. Lighthouse is a crowdfunding application where users can make donations in Bitcoin to projects.

2.5.2 Ethereum

Ethereum is an open-source blockchain application platform [38] proposed by co-founder Vitalik Buterin [39] in 2013 in his white paper [40]. The decentralized platform runs smart contracts, which are unstoppable application transactions.

Inspired by Bitcoin, Buterin came up with a platform to expand the limited financial use cases available in the Bitcoin blockchain. Ethereum is a programable blockchain. Protocols run on the Ethereum Virtual Machin (EVM) [41]. Applications are created by users in the Turing complete programming language, solidity, and executed on the EVM. When an operation is executed on an EVM, it is simultaneously executed on all nodes in the network.

Applications on Ethereum can either be financial, non-financial or semi-financial. Like Bitcoin, Ethereum also has a native crypto currency, Ether. However, unlike Bitcoin, Ether has a purpose other than simply being a crypto currency. In order to run applications on the Ethereum blockchain, a small fee, or gas price, is required. This is to ensure efficient and economical code, as each computational step in the code requires a certain amount of gas [40].

Whereas Bitcoin only allows users to interact with the blockchain through a set of pre-defined operations, Ethereum allows users to create operations with arbitrary complexity.

Several decentralized applications have been created on top of the Ethereum blockchain. Among these is the Brooklyn Microgrid, which will be further discussed in section 3.1. Other applications include Decentralized News Network [42], where factual news reports are rewarded with tokens and free of censorship; uport [43], an identity system for the decentralized web where users can store their identity and credentials on the Ethereum blockchain.

2.5.3 Hyperledger

Hyperledger consists of over 100 members, including companies such as IBM, Intel, Samsung, J.P. Morgan, American Express and Airbus [30]. It is an open-source platform for blockchains hosted by the Linux Foundation. It consists of multiple blockchains, including Hyperledger Fabric from IBM and Hyperledger Sawtooth from Intel.

The Hyperledger blockchains differ from each other, but all have in common that they do not have any crypto currency. The Linux foundation focuses on open industrial blockchain development:

"*Hyperledger is an open source collaborative effort created to advance cross-industry blockchain technologies. It is a global collaboration, hosted by The Linux Foundation, including leaders in finance, banking, Internet of Things, supply chains, manufacturing and Technology.*" [30]

The Hyperledger Fabric version 1.0 was released in July 2017, and the new version Fabric v1.1 was realeased in March 2018. The blockchain is a base for developing blockchain with modular architecture [44], and aims to be a plug-and-play solution for various applications. Through the smart contract system in chaincode, the application logic is determined.

As of yet, the Hyperledger projects are still fairly new and mostly limited to Proof-of-Concept (PoC) testing [45]. The finance sector is one of the industries where the Hyperledger is in the PoC stage. Some of the benefits of using a distributed ledger technology in the financial industry includes: "*streamlined settlement, improved liquidity, supply chain optimization, increased transparency, and new products/markets*"

Following is a list of PoC projects that have been developed within the finance sector using Hyperledger technology:

- Bank-to-Bank transfers [46]
- eVoting [47]
- Peer-to-peer energy trading [48]
- Cross-border trade operations [49]

In 2016, transport company Maersk partnered with IBM to create a platform where blockchains are used in the cross-border shipping processes [50]. To goal is to provide a better and more efficient solution for tracking information and handling documentation in the shipping industry. The system is built using Hyperledger Fabric. Each shipment will have its own blockchain, containing only transactions and information relevant to that shipment. Through an API, participants can connect to the system and monitor the shipment. However, participants will only have access to transactions relevant to them, thus ensuring privacy in the blockchain.

2.5.4 Comparison of Commercial Blockchains

Table 2.3 summarizes the key features of the previously discussed blockchains:

Table 2.3: Comparison between blockchains [13, 41, 30]

Blockchain	**Bitcoin**	**Ethereum**	**Hyperledger Fabric**
Founded	2009	2015	2017
Crypto currency	Bitcoin	Ether	Non
Consensus	PoW	PoW, PoS	PBFT
Permission	Permissionless	Permissionless	Permissioned
Public access	Public	Public and Private	Private
Smart contracts	Non	Smart Contracts	Chaincode
Language	C++	Go, C++, Python	Go, Java

2.6 Smart Contracts

The idea of smart contracts was first proposed by Nick Szabo in 1996, stating that *"Smart contracts combine protocols, users interfaces, and promises expressed via those interfaces, to formalize and secure relationships over public networks. This gives us new ways to formalize the digital relationships which are far more functional than their inanimate paper-based ancestors. Smart contracts reduce mental and computational transaction costs, imposed by either principals, third parties, or their tools [51]"*.

Smart contracts can be compared to vending machines in regards to their ability to self-execute given that the right terms are met. For instance, a vending machine will only provide the user with the goods, given that the purchased item is in stock and that the user has put in enough money. Just like with smart contracts, it is an event based mechanism that is executed without the need of a third party.

The Ethereum blockchain was built with smart cotnracts as the main objective. In this case, a smart contract is code which enable self-enforcing applications, through a pre-defined set of rules in the code. The smart contract code is stored in blocks which in turn become part of the blockchain. The smart contracts are used to establish rules between peers. In order to be able to create Turing complete [1] contracts, a new programming language, solidity [41], was developed for use on the Ethereum platform. The software program adds layers of information onto digital transactions being executed on a blockchain. It allows for more complex transactions than simply exchanging digital tokens for a product or service.

However, smart contracts are not without issues. The Decentralized Autonomous Organization (DAO), an entity based on Ethereum, implemented a crowd funding

[1] A Turing complete programming language is one that can solve any problem that a Turing machine can.

platform that raised $ 150 million. Due to shortcomings in the implementation of the contracts, hackers were able to withdraw $ 60 million from the funds [52]. This shows that smart contracts can only be as smart as the people coding them. Other issues include the difficulties to update or alter contracts once they are stored on the blockchain, due to their immutable properties. If a bug in the contract is detected, it is not easily patched.

In summary, smart contracts are just computer code that is stored on the blockchain, and runs when the right conditions occur. The key characteristics can be summarized as follows:

- Contracts consist of pre-defined terms and contract-parties.
- Contract execution is triggered by events, such as received transaction information.
- Terms of contract dictate where to move value when terms are met
- Digital assets are automatically settled on the chain once a contract is executed.

Chapter 3

Related work

There already exist some examples of blockchains being used in the energy market.

Using blockchain in the energy market was first proposed by Mihaylov et al. [4]. NRGcoin was introduced as digital currency for buying and selling energy through smart contracts. However, the transactions are not done in a P2P approach.

There are several companies emerging, that are developed for P2P energy trading. Three of these, all entering the market in 2016 or later, will be further discussed.

3.1 Brooklyn Microgrid

The Brooklyn Microgrid is a project owned by LO3, where some neighbors in Brooklyn, New York trade energy [5]. This is done in a peer-to-peer manner, over the blockchain, thus removing the middleman. Residents who have installed solar panels on their roof tops, can sell any excess energy to their neighbors. The first transaction occurred in April 2016, and is [53, 54] the first ever energy transaction made on a blockchain.

The company started working with the public blockchain Ethereum [55, 54], which was the first blockchain to make a non-financial transaction. However, they quickly realized that this was not a feasible solution, and decided to make their own, private blockchain.

The microgrid was developed by the Siemens Digital Grid Division, while the blockchain platform was developed by LO3 Energy. Each participant in the project has a meter installed. These meters communicate with each other, and other smart devices. Furthermore, they measure the energy production and consumption. The key factor, however, is that these meters form the blockchain [55, 56]. Transactions from each meter is stored on the blockchain, while all meters contribute with the computational power necessary to run the blockchain and validate the transactions.

Mengelkamp et al. [57] presented a case study of the Brooklyn Microgrid. The project consists of both a virtual platform and a physical microgrid. The microgrid is built in parallel with the existing grid, and is able to uncouple from the traditional gird in case of power outages. The virtual platform is the technical infrastructure, and runs a private blockchain. The virtual layer is where all the information of the network is transferred.

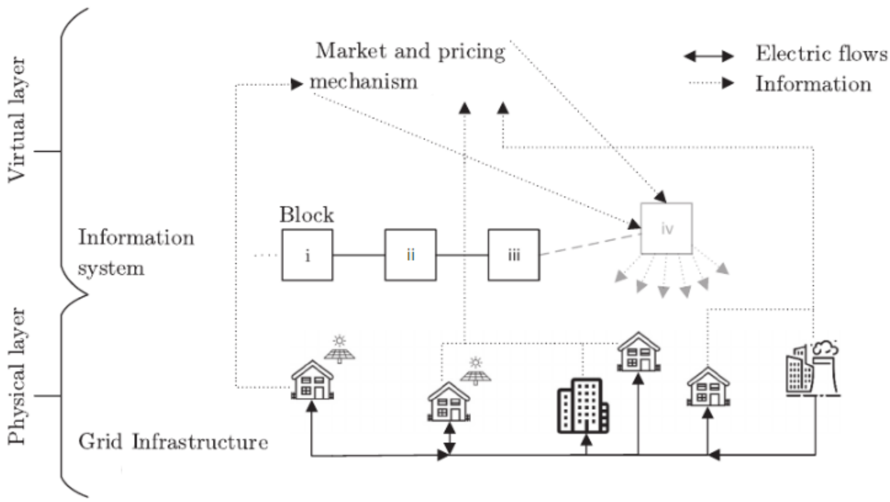


Figure 3.1: High-level topology of the Brooklyn Microgrid [57].

3.2 NAD Grid

NAD Grid is a platform for peer-to-peer energy transactions over the blockchain, based in Silicon Valley [58]. The company focuses on reducing carbon footprint through their Selective Sourcing technology [59].

The software platform is built upon the physical grid, and they aim to partner with existing utility companies [58], who own the grid, to provide a platform that allow users to trade electricity in real-time over the NAD Exchange [59]. As of March 2018 [58], the company has developed a prototype and is currently working on partnering with a utility company to provide a pilot project.

As explained in the NAD Grid whitepaper [48], the platform can be divided into three core components:

- Consortium Blockchain for electricity exchange

- Selective Sourcing
- The Eden token

Each of these components will be further discussed.

The **Electricity Exchange** is where the electricity is traded. Through the app or website, the real-time market price can be seen, and smart contracts can be initiated between peers. The smart contract automatically executes payments on the blockchain with zero fees. The consortium blockchain keeps track of the balance for each user. All transactions between peers are stored on the blockchain, and the balance for each participant in the transaction will be automatically updated. Users can at any time verify their balance by auditing the ledger.

Selective Sourcing, which is a NAD Grid invention, requires electricity producers to label their energy production with a carbon footprint, based on the amount of greenhouse gases emitted in kilograms per kilowatt-hour. Consumers can then specify the cleanliness of the electricity they wish to purchase. Consumers can specify a carbon footprint grade they want, and the selective sourcing technology will automatically find the cheapest available electricity, based on the constraints.

Eden tokens, which are part of the Ethereum blockchain, are used to pay service fees for the Selective Sourcing service. The consumed electricity is paid in fiat currency. Each token allows a certain amount of electricity to be sourced with Selective Sourcing.

3.3 Power Ledger

The Australian company, Power Ledger, is a peer-to-peer marketplace for renewable energy where neighbors can trade their excess solar power without a middleman [60]. It was founded in 2016, and did its first application beta testing in 2017. Wanting to utilize the smart contract functionality of Ethereum, part of the platform is built on top of the Ethereum blockchain. The following description of the system is based on the Power Ledger whitepaper [61].

The Power Ledger platform consists of two blockchains, each with its own token:

The POWR token is traded on the public Ethereum blockchain, this is used by participants to gain access to the platform, and serves as the fuel of the Power Ledger Ecosystem. A user is always required to have a certain amount of POWR tokens in order to be allowed access to the trading Platform. Furthermore, POWR tokens can be traded for Sparkz tokens.

The Sparkz token is used for the actual electricity transactions and exist on a consortium blockchain. The token can be exchanged for local fiat currency on the Application Host, which is also where applications running on the platform can be accessed. In Australia, 1 Sparkz equals 1 cent AUD.

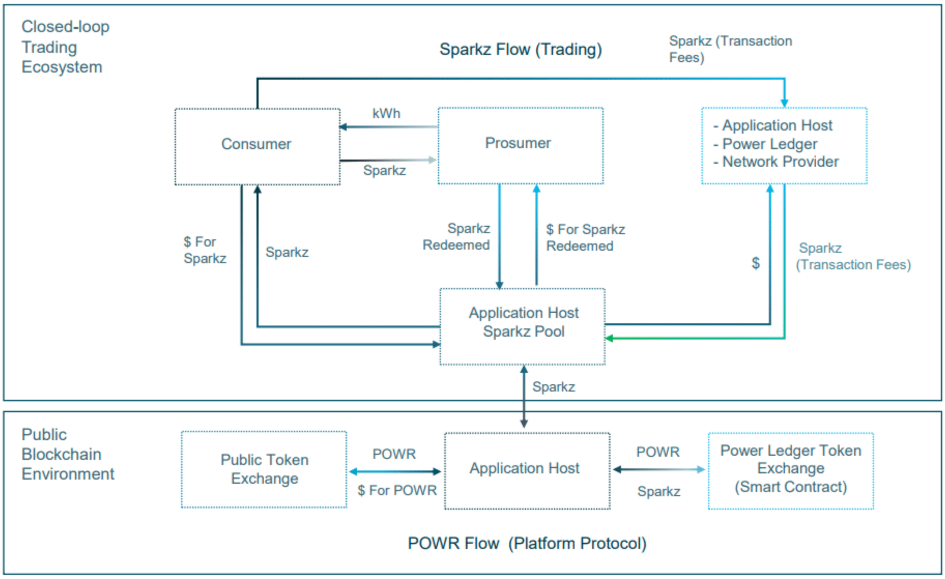


Figure 3.2: Power Ledger Platform [60].

Through the Power Ledger application layer, prosumers and consumers can trade electricity directly with each other. This is done by initiating a smart contract. Meter readings are done by smart meters, and recorded in the blockchain, providing an audit trail for the participants.

Chapter 4

Functional Specifications

This chapter describes the functional specifications of a system for settlement in a microgrid. The specifications are divided into three categories: application from the user's perspective; application from computer's perspective; and the blockchain.

Each node consists of a smart meterfor registering consumption and production of electricity. The smart meter is connected to the node's computer. The computer receives data from the smart meter and processes the data before passing it on to the blockchain, which also runs on the computer. Nodes are uniquely identified by their ID.

The system consists of the following participants:

- Consumers purchasing electricity.
- Prosumers who consume electricity, and sell excess electricity from their own production. Prosumers can also purchase electricity from others.
- Public producers delivering electricity on demand through generators, batteries, or power transmitting cables.

Having power delivered by public producers is a costly solution, and should be avoided. Participants can be discouraged from this solution by setting extreme prices on electricity from these sources.

4.1 User Interface

This section describes how the user interacts with the system.

1. Users connect to existing nodes on the Network, given an IP address and a port number. The user also chooses a port to run the application on.

2. A website lets users set up smart contracts and tracks their energy flow.
3. The website requires a login where users are identified by their node ID.
4. Prosumers with surplus electricity to sell, put up their availability on the website.
5. Consumers who want to purchase electricity can query available producers and initiate a smart contract.
6. Users can monitor how much electricity they produce and consume in real-time.

4.1.1 Use Case

Use cases for how prosumers and consumers interact with the system are described below.

Prosumer

A user who produces excess electricity can choose to sell this electricity to neighbors connected to the microgrid. The user connects to the network grid and is given a unique public/private key pair, which is the node ID and a corresponding password. The user can log in to the website and advertise the available electricity to other users on the network. When queried by consumers about availability, the users can set up a smart contract. The user can log in to the website and monitor how much electricity they consume, and how much they produce to the grid, as well as the electricity price. If a prosumer does not meet the requirements of a contract, he or she must pay a fee corresponding to the difference between the price the prosumer is selling at, and the price of available energy.

Consumer

Users wishing to purchase electricity from their neighbors can connect to the microgrid network. After logging in to the website with their given node ID and password, they can query other users for available electricity. The consumer can set up a smart contract with a prosumer. Consumers can at any time log in to the website and monitor how much electricity they consume at minute intervals, and at what price. If the consumer decides to use less energy than what was specified in the contract, he or she must pay a fee corresponding to what the producer is losing in profit.

4.2 Application Interface

This section describes how the computer handles incoming data from the users and connected smart meters, forwarding the data to the blockchain, and settling the transaction between users.

1. The computer is connected to a smart meter and receives information about a node's consumption and production of electricity at periodic intervals.

2. The machine passes the readings on to the blockchain for storage.

3. When two users initiate a smart contract, the machine passes it on to the blockchain for validation and storage.

4. New readings from the smart meter are processed on the website and added to the graphs for consumption and production.

5. Settlement is done every time new readings occur. Based on valid contracts in the system and data from the readings, each node's bill is updated reflecting the latest transactions.

4.2.1 Use Case

Following are use cases for when the computer receives a new meter reading, how consumption and production of electricity are monitored, and how smart contracts are processed.

New Meter Reading

Once, every minute, the computer receives measurement readings from the smart meter. The readings include the node ID of the smart meter, and amount of electricity produced and consumed since the last reading. The information is then passed on to the node's blockchain for storage. The settlement module in the applications settles the new readings based on the valid contracts in the system.

Monitoring Consumption and Production

When new measurements are received from the smart meter, the readings become available to the user through the monitoring display on the user interface. A super user can view graphs for all nodes in the network. Individual nodes can only see their own graph, by logging in with the node ID.

New Contract

When two users initiate a contract through the user interface on the web site, it is passed to the blockchain for validation and storage. When new meter readings are registered, the system iterates through valid contracts to settle the new transactions

4.3 Blockchain

The blockchain acts as the back-end service to support the requirements given in sections 4.2 and 4.1.

1. The application sends two types of input to the blockchains, a smart contract between two users and electricity transactions. There are two types of blockchains. One for storing smart contracts, and one for storing electricity transactions.
2. The blockchains are distributed between all the nodes in the network.
3. The nodes broadcast their individual transactions across the network, while new smart contracts are sent directly to the consensus leader.
4. The leader of the blockchain proposes a new blocks when data is available.
5. The proposed block is broadcasted to the consensus nodes, who validate the block and the transactions.
6. If a majority of the nodes deem the block valid, all nodes will add the new block to their blockchain.
7. When the application is settling new transactions, valid smart contracts in the blockchain are triggered and used in the settlement process.

4.3.1 Use Case

How the blockchain handles smart contracts and electricity transactions are described in the use cases below.

Smart Contract

When two users decide to initiate a smart contract, it is sent to the blockchain for validation. The users sign the contract with a digital signature - their private key. The signature can later be verified with the user's public key. When the smart contract is passed to the blockchain module, it is added to a block and verified by the nodes before the block is stored in the blockchain.

Electricity Transactions

New electricity transactions from all network nodes are passed to the blockchain layer every minute. New transactions from each node are broadcasted throughout the network. The current leader adds all new transactions to a block, which is validated by the nodes before it is stored in the blockchain.

Chapter 5

Design

The system design is specified in this chapter. The first section illustrates the system architecture, and how the different layers in the system interact on a top-level. The last section is a detailed description of how the main modules in the system should behave.

5.1 System Architecture

The blockchain layer and the application layer design are both illustrated in this section. The interaction between the layers is illustrated at the end of the section.

5.1.1 Blockchain Layer

The relation between the modules of the blockchain layer can be seen in figure 5.1. The main modules of the system are the *node*, *consensus* and, *network* modules. Whereas the *storage*,*messages*, and *block* modules are helper modules. The *node* object in the *node* module is a subclass of the *PeerManager* in the *network* module, which allows the *node* object to directly use methods in the *network* module to communicate with other nodes.

5.1.2 Application Interaction with Blockchain

5.2 Module Design

The individual modules in each of the are explained in further detail in this section.

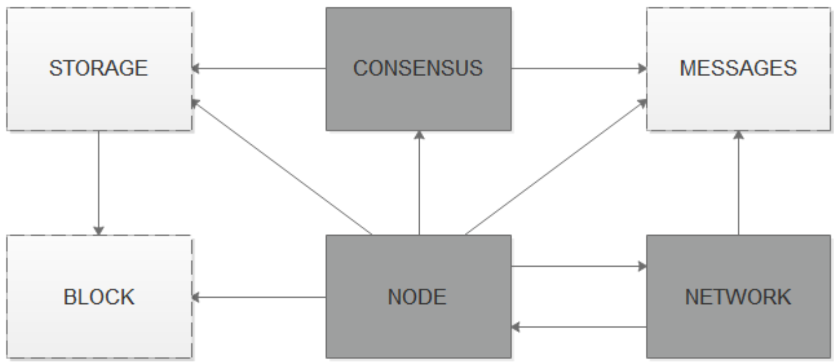


Figure 5.1: Connection between modules in blockchain layer.

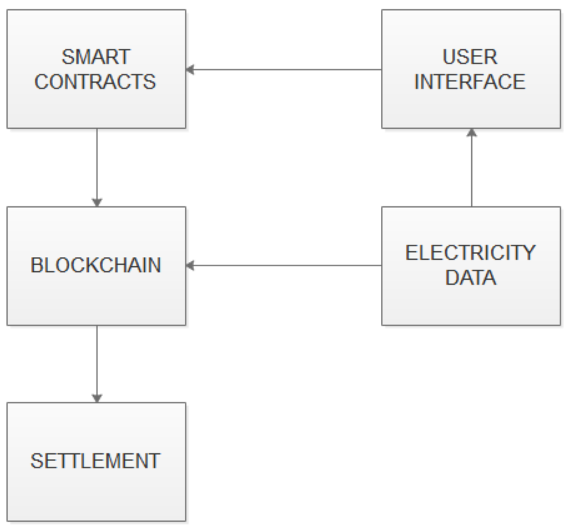


Figure 5.2: Interaction between application and blockchain.

5.2.1 Smart Contract

When a consumer and prosumer initiate a smart contract, the terms of the contract must include the following.

1. The start time of the contract.
2. The end time of the contract.

3. The ID's of the prosumer and consumer.
4. The minimum amount of electricity transacted between the parties of the contract.
5. Digital signatures from both parties of the contract.

All smart contracts are stored in their own blockchain to increase read efficiency. The contracts are verified with the public keys of the nodes, before it is stored in the blockchain.

The smart contract API is callable from the website, and is triggered when two parties initiate the contract. Any node in the system can only have one active contract at a time. New transactions trigger settlement based on smart contract.

5.2.2 Blockchain

There are two blockchains for the microgrid, one for storing all electricity transactions in the system, and one for storing all smart contracts. The blockchains are the back-end services that enable the settlement process. The purpose of the blockchain is that two different parties cannot claim the same unit of produced energy, or the transaction payment.

5.2.3 Settlement

When the system receives information of consumed and produced electricity of a node, the smart contract is self-enforcing in the manner that these events trigger functions that control the settlement.

Energy trading is a very complex task, thus four assumptions are made for the settlement module in this system:

- During any interval, the amount of electricity consumed in the system equals the amount of electricity produced in the system.
- Any participant in the network has one, and only one, contract with another participant in the system at any given time.
- If the consumer of a contract has consumed more electricity than the producer of the contract has produced, the excess consumed electricity is produced by the pure producers in the system.
- If a prosumer produces more electricity than is consumed by itself or the consumer in the contract, during an interval, it is assumed that the electricity is stored in batteries and not part of the settlement process.

If prosumer A has a smart contract with consumer B, and the system registers that these nodes have produced and consumed electricity during any interval in the duration of the contract, node B's bill will register that it owes node A for the consumed electricity of the period, and likewise node A's bill will show that node B owes money for the electricity. Each node in the system has a bill of how much the node owes other nodes in the system, and how much other nodes owe this node. The bills are accumulative and assumed settled at regular intervals, e.g. each month.

5.2.4 Consensus

The consensus protocol is modeled after the Raft protocol. Five nodes are in charge of the consensus process in the consortium blockchains. The reason why only five nodes should participate in the consensus process is to reduce the message overhead in the system. The consensus process has a randomly selected leader. Any node can be part of the consensus process, and any node can become leader. If a node participating in the consensus goes offline for some reason, another node will take its place. Nodes in the system send their transactions and contracts to the consensus leader, who then initiates the validation process by creating a block. If consensus is reached among the validating nodes, the block is stored in one of the blockchains, depending on if it contains electricity transaction or a smart contract.

5.2.5 Website

The website is the user interface to the system. A user is either a prosumer or a consumer in the microgrid, or the special case of a super user, who can access all the information of the system. Users may log in to their own profile to monitor real-time, and past, consumption and production of electricity. The log in is done with the user's public and private keys. The website has a trading platform where prosumers advertise how much electricity they are selling. Consumers can inquire the prosumers to make a contract. The contract is finalized and sent to the consensus leader when both parties have signed the contract with their private keys.

Chapter 6

Implementation

This chapter describes the implementation of the system in this thesis. The first section details the software used in the implementation. The rest of the chapter describes how the individual modules of the system are implemented.

6.1 Software

Following is a list of the resources used in this system implementation:

- Python for implementation of the system
- Python framework Twisted for network communication
- Flask for web applications
- ECDSA for digital signatures and verification

6.1.1 Python

Python [62] was chosen as the programming language for the system implementation in this thesis. This is due to Pythons multipurpose abilities, and the intuitive syntax and programming style, which enables a rapid program development. Python also possesses characteristics like object-orientation, as well as being modular and dynamic. There exists a wide range of modules and libraries in Python. One of these libraries is the unit test framework, which supports test automation and eases code testing.

6.1.2 Twisted

Twisted [63] is a networking engine written in Python. Some of the main components of the Twisted library are described below:

- **Reactor**: The reactor reacts to events in a loop and dispatches them to predetermined callback functions that handle the events. The event loop runs endlessly, unless it is told to stop.
- **Protocols**: Each protocol object in Twisted represents one connection. Protocols handle network events in an asynchronously manner. The protocol is responsible for handling incoming data, and new connections and lost connections of peers.
- **Factory**: Protocol instances are created in the factory, one for each connection. The factory utilizes the protocol for communication with its peers. Information that is persistent across connections is stored in the factory.
- **Transport**: A transport is a method that represents the actual connection between the two endpoints in a protocol, e.g. a TCP connection. The transport is used for communication between the two endpoints, as it writes data from one connection to the other.

6.1.3 Flask

Flask is a microframework for web development written in Python [64]. Flask is a lightweight WSGI (Web Server Gateway Interface) web application framework that is designed for quick development. The Flask API is easy to use due to the frameworks extensive documentation, and due to the fact that there are no additional tools or libraries needed.

6.1.4 ECDSA

The ECDSA library is an implementation of the cryptography algorithm written in Python [65]. The library creates key pairs for signing messages and verifying the signatures, based on the ECDSA algorithm. Signatures are created by using the private signing key on the message that is to be signed. The signature is verified by using the public verifying key, which corresponds to the signing key. The verification method ensures that the unsigned message is the same as the message verified by the verifying key after it is signed with the signing key, or raises a *BadSignatureError*.

6.2 Blockchain Layer

This section describes the main modules implemented in the blockchain layer.

6.2.1 Block Module

The block module consists of a *Block* class. The attributes of the class are the index of the block, which is the number of the block in the blockchain where the genesis block starts at 0; the hash of the block immediately preceding the block; a timestamp of when the block was created; the transactions included in the block; and the new hash of the block.

The block hash is calculated using the python hashlib [66] library. It uses SHA-256 hash algorithm based on the index, previous hash, timestamp and transactions in the block, thus creating a unique hash for every block. The *hexdigest* method is used to return a string object of double size, containing only hexadecimal digits, for better readability.

Other methods in the class include *validate_block* for validation of a new block, based on the previous block: *propose_block* to create a new block, based on the previous block and the current time; and *assert_equal* to verify that two blocks are identical.

6.2.2 Network Module

A peer-to-peer(p2p) network is implemented in the network module, using the Twisted [63] framework.

The initial network node starts a server, and a client that connects to the server. Other nodes also start a server on a specified port number and a client which connects to a server already running on a given IP address and port number.

The module consists of two classes, a *PeerManager* and a *Peer*. The *PeerManager* class is a Twisted factory, and is responsible for storing information about the peer, which is persistent between connections. This includes attributes such as a dictionary containing all connections to other peers, methods for adding and removing peers to the dictionary, as well as a method for starting a new client that connects to a new peer's server.

Peer is a subclass of the Twisted protocol *IntNStringReceiver*. This means that each received message is a callback to the method *stringReceived*. The *Peer* class also keeps track of information in a connection between two peers. This includes a method for discovering when the connection is lost. The main method of the *Peer* class is the *stringReceived* method. Based on what message type was received, the method decides what to do with the message.

The initial message sent by a client, node A, connecting to a new server, node B, is the *hello* message. This includes the client's node id, IP address, and host port which is information the server on node B keeps track of for all its peers. If the connection is successful, the server on node B acknowledges the message by sending its own node id, IP address, and port number for node A to store. Server B proceeds by sending a message containing information about all its peers to node

A. Node A then starts a new client for all the peers it is not already connected to and repeats the process described above.

Other messages received are processed in the factory, and further handled by the *Node* object.

6.2.3 Node Module

The node module consists of a *Node* class, which is a subclass of the *PeerManager* class. The main component of the *Node* class is the state machine, which is triggered by the reactor making a *LoopingCall* at periodic intervals.

Every time the *state_machine* method is executed, the network leader sends out an *append entries* RPC to all its followers. This lets the followers know that the leader is still operating. If new transactions are available, the leader creates a new block including these transactions, and proposes the block to its followers. If a follower finds a block valid, its stores the block in its log of proposed blocks during the next execution of the *state machine* method.

The leader keeps a timer on the proposed block. If a timeout occurs before a majority has validated and accepted the block, the leader steps down, and a new election for a leader will start once the *leader election timeout* occurs. However, if the majority validates and accepts the block before the timeout occurs, the leader will add the block to the blockchain, and notify its followers to do the same.

6.2.4 Consensus Module

The consensus module used in this system is Raft.

The consensus module consists of a *Validator* class. A *Validator* object is created by the *Node* object, to handle the validation and consensus in the blockchain. Once a *Validator* object is created, a *leader election timer* starts. The timeout is cancelled if the node receives a message from a leader. If the timeout occurs, the *start leader election* method is called. A node promotes itself to a candidate, starts a new term and votes for itself as leader before requesting votes from its peers with the *request vote* RPC.

A follower receiving a *request vote* RPC will vote for the candidate if it has not already vote in that term or not voted for someone else. The follower will also verify that the candidate's blockchain log is at least as up to date as its own before casting the vote. If the candidate receives a majority vote it will establish itself as leader by sending out an *append entries* RPC.

Another possible outcome of the election process is that the candidate does not receive a majority vote before the election timeout occurs. It will then either promote itself as a candidate and start a new term, or receive a *request vote* RPC from another candidate, who has started a new term.

The third outcome is that several nodes become candidate at the same time. If a candidate receives an *append entries* RPC from a different node, it will step down and become a follower.

As previously mentioned, leaders send out *append entries* RPCs from the *Node* object. Followers respond to the RPC in the *Validator* object. With every RPC, the leader includes the previous log index and log term. In the *respond append entries* method, a follower checks if it has this entry in its log and responds accordingly. If there is no entry, the leader decreases the index until a match is found. If there is a conflicting entry, the follower deletes its own entry and writes the leaders entry in the log.

If the *append entries* RPC includes a new proposed block, the follower will validate the block and write the block to the log during the next run of the *state machine*.

6.3 Application Layer

This section includes descriptions of modules implemented in the application layer of the system.

6.3.1 Settlement

Settlement occurs based on existing smart contracts in the system. The protocol is triggered by the blockchain leader every time there is new transaction information in the system that has been verified and added to a block in the blockchain. The settlement algorithm that is implemented is fairly naive, and based around three assumptions given in section 5.2.3. An outline of the algorithm can be seen in Algorithm 1.

6.3.2 Smart Contracts

Smart contracts enable automatic transfer of assets, once conditions are met. Thus, in contrast to traditional contracts, smart contracts do not only define the terms and conditions of an agreement, they also provide a method for enforcing the agreement.

6.3.3 User Interface

The user interface was not integrated with the rest of the system, rather a interface layout was outlined as seen from the consumers perspective. The interface consisted of a web page with two menu options: one for monitoring consumed and produced electricity in real-time; and one to create smart contracts based on prosier availability.

Algorithm 1: Naive settlement algorithm

Result: walled accounts for all nodes updated
buyer bought

```
foreach buyers and sellers in all contracts do
    if seller sold less than 0 then
        seller bought required electricity from pure producer
        buyer bought required electricity from pure producer
    else if seller sold is 0 and buyer bought is more than 0 then
        buyer bought all electricity from pure producer
    else
        if seller sold more than buyer bought then
            buyer bought all required electricity from seller
            assume excess energy stored on battery
        else
            buyer bought all electricity seller sold
            if buyer required more electricity then
                buyer bought required electricity from pure producer
end
```

Chapter 7

Testing

This chapter details how the system was tested. Section 7.1 describes how the complete system was tested, while section 7.2 specifies how the individual modules of the system were tested.

7.1 System Test

A functional test was run on the complete system, using pseudo-random simulation data. The test approach is summarized below:

- Four prosumer nodes with 48 hours worth of test data for produced and consumed electricity, given in kWh per minute. Each node periodically read the test data from a CSV (Comma Separated Value) file. The four nodes were run as different processes on the same computer.

- Smart contracts were manually constructed in pairs between the node, with one node selling, and one node buying electricity per contract.

- Transactions were settled according to the settlement module described in section 6.3.1. For simplicity, the price of 1 kWh was set to 1 NOK, regardless of the production source.

- All transactions were stored in the blockchain. Transactions from all nodes during a given interval were stored in the same block.

7.2 Module Testing

7.2.1 User Interface

Tests were executed on the implemented functionality in the user interface. The monitoring of consumed and produced electricity of a node was tested using simulated data stored in a CSV file.

For the smart contract API, a simple table of producer availability was constructed using arbitrary data, and a form for consumers to initiate a contract was created.

7.2.2 Unittests

Several modules were tested with unittests. Even though the correct behavior of the settlement function can be verified from the system test, a unittest was also created to ease the maintenance process, as it provides a fast and accurate way to verify the correctness of potential changes in the module. The block module was also tested with a unittest for the same reasons.

7.2.3 Network Module

The ability for nodes to communicate over the network is crucial for the system to function. Several aspects of this module were tested:

- Communication with two machines on the same network.
- Communication with two machines on two separate networks.

7.2.4 Consensus

The consensus module is an important feature in order for the system to function with the correct behavior. The following tests were performed to verify this.

- Ability to correct wrong data on a node.
- During normal operation, the consensus model was tested on 10 nodes running as separate processes on two separate computers.
- Adding new nodes under operation.
- Election of new leader after a leader has crashed.

7.2.5 Smart Contract

Signing and validating

Chapter 8

Result

The results from the tests described in chapter 7 are presented in this chapter. The results are further discussed in chapter 9.

8.1 System Results

After running the full system on 48-hours worth of test data, each node produced a blockchain with 2881 blocks, where each block contained four transactions - one for each node. This resulted in a 1.22 MB sized file, which roughly equals 423 bytes per block. The complete result of the test can be found with the source code. To ensure that correct behavior of the system, an extract of the data is shown in figures 8.1 and 8.2. This result is based on the transaction data shown in appendix A. The blockchain in figure 8.1 shows the 10 first blocks in the chain, starting with the genesis block. Each block contains the index of the block, the time at which is was created, the hash of the previous block in the chain, the transaction data for the latest time interval and the hash of the current block. The transaction data contains the node id, consumed electricity and produced electricity in kWhs, respectively, for each node.

Figure 8.2 shows the settlement between two of the nodes in the network. Each line represents the settlement of one transaction, with the most recent settlement at the top. Negative numbers represent money that is owned to the specified node, by the node who's settlement account is shown. Positive numbers represent money that the specified node owes the node who's settlement account is shown.

The results in figure 8.2 show thatnode 712b259d-3d24-431e-b4b8-e091b3a38ad6, the buyer, owes node 274b2397-508c-419d-aa75-d0a909a80dd1, the seller, 3.22 NOK

```
Index:          1
Previous hash:  0
Timestamp:      1970-01-01 01:00:00
Transactions:
Hash:           1917d9dd5e1a500b32a31975683567b1f16711572e32b0971ba3f0b11c4f2fae

Index:          2
Previous hash:  1917d9dd5e1a500b32a31975683567b1f16711572e32b0971ba3f0b11c4f2fae
Timestamp:      2018-05-28 13:18:44
Transactions:
                ['48cb4cc3-d841-498e-8601-c8794be40dc4', '0.000', '-0.517']
                ['274b2397-508c-419d-aa75-d0a909a80dd1', '0', '-0.043']
                ['712b259d-3d24-431e-b4b8-e091b3a38ad6', '2.122', '-0.496']
                ['b5417b5a-d049-4ab1-ad4e-2150d2c8914e', '0.000', '0.000']
Hash:           403f934a515c8a086a4a0b04da7d078bbe7d809a0829a44b119825b9a7d16cf7

Index:          3
Previous hash:  403f934a515c8a086a4a0b04da7d078bbe7d809a0829a44b119825b9a7d16cf7
Timestamp:      2018-05-28 13:18:47
Transactions:
                ['48cb4cc3-d841-498e-8601-c8794be40dc4', '0.000', '-0.273']
                ['274b2397-508c-419d-aa75-d0a909a80dd1', '0', '-0.169']
                ['712b259d-3d24-431e-b4b8-e091b3a38ad6', '4.714', '-0.497']
                ['b5417b5a-d049-4ab1-ad4e-2150d2c8914e', '0.000', '0.000']
Hash:           dcefc0a662e165ea5fec9a48aee62eaaafd255f38c0dc003c926a610c0367d62

Index:          4
Previous hash:  dcefc0a662e165ea5fec9a48aee62eaaafd255f38c0dc003c926a610c0367d62
Timestamp:      2018-05-28 13:18:50
Transactions:
                ['48cb4cc3-d841-498e-8601-c8794be40dc4', '0.000', '-0.080']
                ['274b2397-508c-419d-aa75-d0a909a80dd1', '0', '-0.352']
                ['712b259d-3d24-431e-b4b8-e091b3a38ad6', '5.151', '-0.212']
                ['b5417b5a-d049-4ab1-ad4e-2150d2c8914e', '0.000', '0.000']
Hash:           0a98b109fc93df2960a92ede703e5541012765f371ef345a9cc84ae432956b12

Index:          5
Previous hash:  0a98b109fc93df2960a92ede703e5541012765f371ef345a9cc84ae432956b12
Timestamp:      2018-05-28 13:18:53
Transactions:
                ['48cb4cc3-d841-498e-8601-c8794be40dc4', '0.000', '-0.249']
                ['274b2397-508c-419d-aa75-d0a909a80dd1', '0', '-0.492']
                ['712b259d-3d24-431e-b4b8-e091b3a38ad6', '5.147', '-0.33']
                ['b5417b5a-d049-4ab1-ad4e-2150d2c8914e', '0.000', '0.000']
Hash:           34e013eec76c53d1ef64087b6b9b70013fcccc8b22fdfdac9185184e061bd13b
```

```
Index:           6
Previous hash:   34e013eec76c53d1ef64087b6b9b70013fcccc8b22fdfdac9185184e061bd13b
Timestamp:       2018-05-28 13:18:56
Transactions:
                 ['48cb4cc3-d841-498e-8601-c8794be40dc4', '0.000', '-0.132']
                 ['274b2397-508c-419d-aa75-d0a909a80dd1', '0', '-0.18']
                 ['712b259d-3d24-431e-b4b8-e091b3a38ad6', '5.117', '-0.129']
                 ['b5417b5a-d049-4ab1-ad4e-2150d2c8914e', '0.000', '0.000']
Hash:            836ce0942e5af6656847be179a7934a8910288d7c512ab047f71dd7791ff4084

Index:           7
Previous hash:   836ce0942e5af6656847be179a7934a8910288d7c512ab047f71dd7791ff4084
Timestamp:       2018-05-28 13:18:59
Transactions:
                 ['48cb4cc3-d841-498e-8601-c8794be40dc4', '0.000', '-0.006']
                 ['274b2397-508c-419d-aa75-d0a909a80dd1', '0', '-0.274']
                 ['712b259d-3d24-431e-b4b8-e091b3a38ad6', '5.083', '-0.224']
                 ['b5417b5a-d049-4ab1-ad4e-2150d2c8914e', '0.000', '0.000']
Hash:            95e9aa9a79886b1aece104ade564d21e68189f0bab04cdad4e8f620bb6300427

Index:           8
Previous hash:   95e9aa9a79886b1aece104ade564d21e68189f0bab04cdad4e8f620bb6300427
Timestamp:       2018-05-28 13:19:02
Transactions:
                 ['48cb4cc3-d841-498e-8601-c8794be40dc4', '0.000', '-0.022']
                 ['274b2397-508c-419d-aa75-d0a909a80dd1', '0', '-0.435']
                 ['712b259d-3d24-431e-b4b8-e091b3a38ad6', '5.12', '-0.019']
                 ['b5417b5a-d049-4ab1-ad4e-2150d2c8914e', '0.000', '0.000']
Hash:            59ca5878061db43bfb7efba09ed7953352ef3f0e44d46ae78b6ad19946af265c

Index:           9
Previous hash:   59ca5878061db43bfb7efba09ed7953352ef3f0e44d46ae78b6ad19946af265c
Timestamp:       2018-05-28 13:19:05
Transactions:
                 ['48cb4cc3-d841-498e-8601-c8794be40dc4', '0.000', '-0.198']
                 ['274b2397-508c-419d-aa75-d0a909a80dd1', '0', '-0.175']
                 ['712b259d-3d24-431e-b4b8-e091b3a38ad6', '5.105', '-0.116']
                 ['b5417b5a-d049-4ab1-ad4e-2150d2c8914e', '0.000', '0.000']
Hash:            8ffdabec8f9e424aedb8b770d2b7469ff128a0785afe8854222252eb5e91ca91

Index:           10
Previous hash:   8ffdabec8f9e424aedb8b770d2b7469ff128a0785afe8854222252eb5e91ca91
Timestamp:       2018-05-28 13:19:08
Transactions:
                 ['48cb4cc3-d841-498e-8601-c8794be40dc4', '0.000', '-0.329']
                 ['274b2397-508c-419d-aa75-d0a909a80dd1', '0', '-0.285']
                 ['712b259d-3d24-431e-b4b8-e091b3a38ad6', '5.113', '-0.157']
                 ['b5417b5a-d049-4ab1-ad4e-2150d2c8914e', '0.000', '0.000']
Hash:            d8491a5d1215ed5110e40891ea01284b46e3cae9281f3e3a066aceefa207ae8f
```

Figure 8.1: 10 first blocks in the blockchain.

```
2018-05-21 00:18:00; {'712b259d-3d24-431e-b4b8-e091b3a38ad6': 3.22, 'Producer': -24.55}
2018-05-21 00:17:00; {'712b259d-3d24-431e-b4b8-e091b3a38ad6': 3.22, 'Producer': -21.5}
2018-05-21 00:16:00; {'712b259d-3d24-431e-b4b8-e091b3a38ad6': 3.22, 'Producer': -18.4}
2018-05-21 00:15:00; {'712b259d-3d24-431e-b4b8-e091b3a38ad6': 3.22, 'Producer': -15.23}
2018-05-21 00:14:00; {'712b259d-3d24-431e-b4b8-e091b3a38ad6': 3.22, 'Producer': -11.99}
2018-05-21 00:13:00; {'712b259d-3d24-431e-b4b8-e091b3a38ad6': 3.22, 'Producer': -8.72}
2018-05-21 00:12:00; {'712b259d-3d24-431e-b4b8-e091b3a38ad6': 3.22, 'Producer': -5.54}
2018-05-21 00:11:00; {'712b259d-3d24-431e-b4b8-e091b3a38ad6': 3.22, 'Producer': -2.3}
2018-05-21 00:10:00; {'712b259d-3d24-431e-b4b8-e091b3a38ad6': 3.22, 'Producer': 0}
2018-05-21 00:09:00; {'712b259d-3d24-431e-b4b8-e091b3a38ad6': 2.87, 'Producer': 0}
2018-05-21 00:08:00; {'712b259d-3d24-431e-b4b8-e091b3a38ad6': 2.4, 'Producer': 0}
2018-05-21 00:07:00; {'712b259d-3d24-431e-b4b8-e091b3a38ad6': 2.11, 'Producer': 0}
2018-05-21 00:06:00; {'712b259d-3d24-431e-b4b8-e091b3a38ad6': 1.94, 'Producer': 0}
2018-05-21 00:05:00; {'712b259d-3d24-431e-b4b8-e091b3a38ad6': 1.5, 'Producer': 0}
2018-05-21 00:04:00; {'712b259d-3d24-431e-b4b8-e091b3a38ad6': 1.23, 'Producer': 0}
2018-05-21 00:03:00; {'712b259d-3d24-431e-b4b8-e091b3a38ad6': 1.05, 'Producer': 0}
2018-05-21 00:02:00; {'712b259d-3d24-431e-b4b8-e091b3a38ad6': 0.56, 'Producer': 0}
2018-05-21 00:01:00; {'712b259d-3d24-431e-b4b8-e091b3a38ad6': 0.21, 'Producer': 0}
2018-05-21 00:00:00; {'712b259d-3d24-431e-b4b8-e091b3a38ad6': 0.04, 'Producer': 0}
```

(a) Settlement for node 274b2397-508c-419d-aa75-d0a909a80dd1

```
2018-05-21 00:18:00; {'274b2397-508c-419d-aa75-d0a909a80dd1': -3.22, 'Producer': -62.03}
2018-05-21 00:17:00; {'274b2397-508c-419d-aa75-d0a909a80dd1': -3.22, 'Producer': -60.18}
2018-05-21 00:16:00; {'274b2397-508c-419d-aa75-d0a909a80dd1': -3.22, 'Producer': -58.24}
2018-05-21 00:15:00; {'274b2397-508c-419d-aa75-d0a909a80dd1': -3.22, 'Producer': -56.42}
2018-05-21 00:14:00; {'274b2397-508c-419d-aa75-d0a909a80dd1': -3.22, 'Producer': -54.55}
2018-05-21 00:13:00; {'274b2397-508c-419d-aa75-d0a909a80dd1': -3.22, 'Producer': -52.69}
2018-05-21 00:12:00; {'274b2397-508c-419d-aa75-d0a909a80dd1': -3.22, 'Producer': -50.67}
2018-05-21 00:11:00; {'274b2397-508c-419d-aa75-d0a909a80dd1': -3.22, 'Producer': -48.68}
2018-05-21 00:10:00; {'274b2397-508c-419d-aa75-d0a909a80dd1': -3.22, 'Producer': -46.68}
2018-05-21 00:09:00; {'274b2397-508c-419d-aa75-d0a909a80dd1': -2.87, 'Producer': -42.61}
2018-05-21 00:08:00; {'274b2397-508c-419d-aa75-d0a909a80dd1': -2.4, 'Producer': -38.1}
2018-05-21 00:07:00; {'274b2397-508c-419d-aa75-d0a909a80dd1': -2.11, 'Producer': -33.43}
2018-05-21 00:06:00; {'274b2397-508c-419d-aa75-d0a909a80dd1': -1.94, 'Producer': -28.62}
2018-05-21 00:05:00; {'274b2397-508c-419d-aa75-d0a909a80dd1': -1.5, 'Producer': -23.95}
2018-05-21 00:04:00; {'274b2397-508c-419d-aa75-d0a909a80dd1': -1.23, 'Producer': -19.36}
2018-05-21 00:03:00; {'274b2397-508c-419d-aa75-d0a909a80dd1': -1.05, 'Producer': -14.55}
2018-05-21 00:02:00; {'274b2397-508c-419d-aa75-d0a909a80dd1': -0.56, 'Producer': -10.22}
2018-05-21 00:01:00; {'274b2397-508c-419d-aa75-d0a909a80dd1': -0.21, 'Producer': -5.63}
2018-05-21 00:00:00; {'274b2397-508c-419d-aa75-d0a909a80dd1': -0.04, 'Producer': -1.58}
```

(b) Settlement for node 712b259d-3d24-431e-b4b8-e091b3a38ad6

Figure 8.2: Settlement between two prosumer nodes that have initiated a smart contract.

after 19 minutes. Both nodes have consumed a considerable amount of electricity generated from the pure producers.

8.2 Module Results

8.2.1 User Interface

The results from the tests run on the user interface can be seen here. Figure 8.3 shows how the consumption and production of electricity can be viewed in real-time for each node. Figure 8.4 show how the producers can advertise their available excess electricity, and an approach for creating smart contracts from the buyers point of view.

8.2.2 Unittests

8.2.3 Network Module

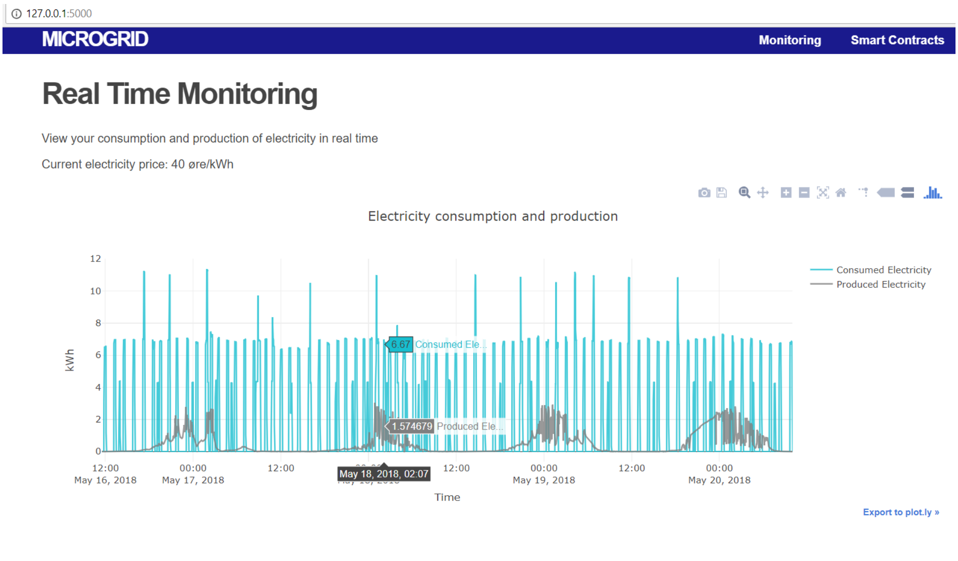
Success for two machines on same network

Fail for two machines on different network, due to port forwarding issues

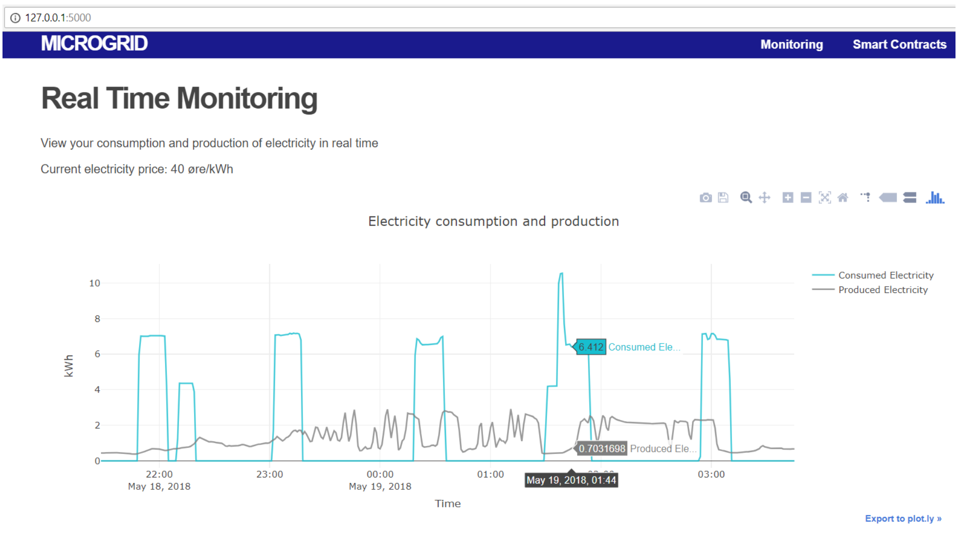
8.2.4 Consensus

8.2.5 Smart Contract

Image of signing/validation



(a)



(b)

Figure 8.3: Real-time monitoring of consumed and produced electricity displayed on user interface. (a) shows the whole timeline and (b) shows a zoomed extract.

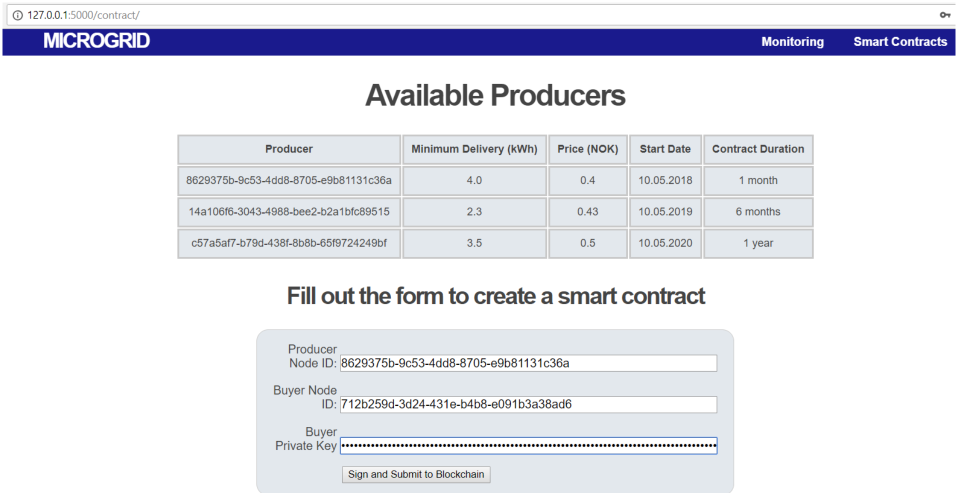


Figure 8.4: Availability producers selling excess electricity.

```
2018-05-15 09:33:21+0200 [-] Added peer: 8629375b-9c53-4dd8-8705-e9b81131c36a 192.168.0.16 8001
2018-05-15 09:33:22+0200 [-] Added peer: c98b06cb-6c88-49ea-ac9f-74e224a69776 192.168.0.20 8002
```

Figure 8.5: Network communication between two computers on the same network.

Chapter 9

Discussion

9.1 Interpretation of Results

The results from the system test show that a blockchain may be used to settle the value of the energy flowing in the system.

Ensure settlement by referring to transactions stored on blockchain consensus - cluster change

9.2 Evaluation of system

In this section, the system implementation will first be evaluated based on the functional specifications presented in chapter 4, and later compared to existing implementations presented in chapter 3

User Interface

Of the six functional specifications for the user interface in section 4.1 only some specifications are fulfilled or partly fulfilled. The following lists further indicates whether each of the specifications are satisfied or not.

1. The application runs by entering the port for which the application should run on, and the IP address and port number of the node to connect to. This satisfies the first specification.

2. A website has been created that suggests a way to monitor energy flow, and a way to create smart contracts. The website is not operative, but rather created as a proof-of-concept.

3. The website login is not implemented, leaving this specification unfulfilled.

4. No functionality for sellers to put up availability was implemented. The website demonstrated in figure 8.4 was hardcoded, but should in reality be updated dynamically. This could for instance be done through a form similar to the smart contract query.

5. A layout for how the buyers can initiate the smart contract with sellers is demonstrated in figure 8.4. However, this is only shown from the buyers perspective. In order for it to be valid, the contract also needs to be signed by the buyer.

6. The ability to monitor the energy flow in real-time is only partially shown. Figure 8.3 suggests how the layout could be, but it is not tested on real-time data. The back end service of the website needs to store all data for each user. Ideally, this should be taken directly from the blockchain in order to ensure data integrity. However, this might not be feasible as it would require a significant amount of time and computational power to search through the blockchain for all transactions. An alternative approach could be to store electricity data in a separate database.

The user interface requires further work in order to be fully operative. This thesis has merely demonstrated a layout for how this can be achieved, as the user interface was not the main objective in the implementation.

Application Interface

The specifications from the 4.2 section are further evaluated below.

1. As this implementation is only focused around the hardware, no tests have been done using actual data from the smart meters. All tests have been executed based on simulated data stored in a CSV file. However, this solution shows that the system can handle processing the information at periodic intervals.

2. All information about the energy flow in the system is stored in the blockchain, leaving this specification fulfilled.

3. Since the ability to create smart contracts in the user interface was not implemented, the specification of validating and storing smart contracts is not satisfied either. However, the results in section 8.2.5 demonstrate a method for signing and validating smart contracts. This has not been integrated into the system, due to time restrictions. Smart contracts were rather created manually to prove the functionality of the settlement algorithm.

4. Similar to the first specification in this section, and the last specification of the previous section, the new electricity transactions are not processed on the website.

5. The settlement specification is satisfied. The blockchain leader initiates the settlement every time a new block is validated by the network and added to the blockchain. Due to the naive settlement algorithm

Blockchain

The blockchain has been the main focus for the implementation of this system, as this is the fundamental structure that supports the rest of the system. All specifications regarding the blockchain are (partly) fulfilled. As previously mentioned, smart contracts are not integrated into the system, thus affecting the specifications where the smart contracts are involved.

1. The system supports storing electricity transactions in the blockchain, but smart contracts are not supported in the current implementation.

2. The blockchain is distributed between all nodes in the network. The tests show that this can be done with 10 nodes in the system, but should also work for a higher number of nodes.

3. Broadcasting of electricity transactions is implemented. However, due to the same factors as the first specification, the smart contract part of the specification is not implemented.

4. In the current implementation, the leader proposed a new block every time it has transaction data from all nodes in the network for each interval. As the system is tested on simulated data, new transactions are read in to the system every two seconds, and new blocks created thereafter. This specification is satisfied, but some modifications needs to be made to the system for it to work on actual data. In reality, a new block will be created every minute, once transaction data for this period is available to the leader.

5. All nodes in the network participate in the consensus process. Further testing on a bigger network needs to be carried out in order to determine if this is the best course of action. An alternative could be to only have a limited number of nodes participate in the consensus process. This is further discussed in section 9.5.

6. The leader of the blockchain keeps track of how many nodes have validated the new proposed block. Once a majority of the network has accepted it, the leader adds it to the blockchain and notifies the other nodes in the network to do the same. Thus satisfying this specification.

7. As the smart contracts are not stored in the blockchain, the requirement of using them in the settlement process is not satisfied. However, the smart

contracts that were manually created to use in the system test show that new transactions trigger the settlement based on the smart contracts.

9.2.1 Evaluation of Related Implementations

Several implementations that already used blockchains for settlement in microgrids were presented in chapter 3. This section will evaluate what sets the implementation in this thesis apart from these other implementations.

What differs in this solution, compared to the other solutions from the background chapter? What sets this system apart from many of the other related systems, is that there are no tokens.

9.3 Privacy

Privacy is an important aspect of any digital system, but was not prioritized in this implementation. This section presents why privacy needs to be included in a fully functioning system, and how this might be achieved.

In order for a system, such as the one proposed in this thesis, to be applied in the real world, the potential users must be assured that their private data is being adequately secured. In blockchains, there is a fine line between balancing transparency and privacy. The transparency is required in order to validate the transactions on the blockchain. However, it is not desirable that anyone can access user data. Figure 9.1 is taken from the Bitcoin white paper, and shows how blockchains redefine the privacy model. The traditional model where third parties are trusted to handle transactions, hides everything from the public. However, the new privacy model only hides identities from the public, while all transactions are transparent and can be audited by anyone. The implementation in this thesis hides the identities to a certain degree by using UUID as identification. However, this does not completely protect identities, as IP addresses could be tracked and linked to the identities. The benefit of a consortium blockchain, is that transaction transparency can be limited to only the members of the network.

Transparancy/privacy user interface

Issues related to privacy may occur if identities are not properly secured, and transaction data is leaked to, or otherwise obtained by, unauthorized parties such as criminals or companies that exploit the data. E.g. criminals could monitor electricity consumption of a household to detect when the house is empty and thus rob it. With all the recent focus concerning data privacy, willingness to use such a system would diminish if transaction data was sold to companies that for instance used it to analyze user behavior and thereby using it for marketing and advertising.

One way to ensure that unauthorized people are not given access to data on the blockchain, could be to encrypt all the information that is stored on the blockchain,

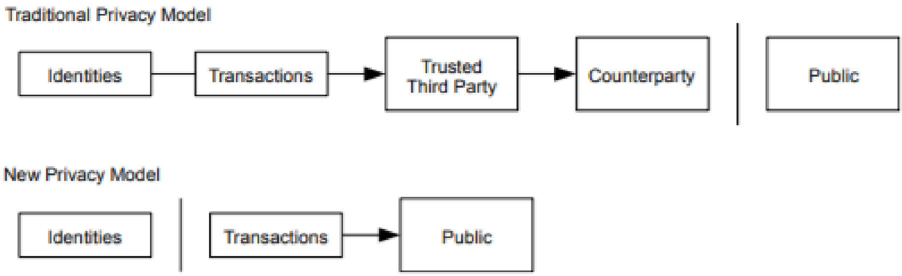


Figure 9.1: Blockchain privacy model [13].

and only grant access to the decryption key to approved participants of the network. However, the encryption and decryption of data is a fairly heavy computationally operation, and leads to more overhead in the system. This also requires that all members of the network are given the decryption key. What would happen if someone accidentally (or purposely) gives away their key information? Such an implementation would require a careful and well tested design.

9.4 Limitations in Implementation

Blockchain technology is still very young, with the first appearance in 2008, in the Bitcoin white paper. The Ethereum platform, launched in 2015, is one of the very first to use the blockchain technology for something else than just crypto currency. In the past couple of years, there has been huge advantages in the field, and many new blockchain applications have been created. Furthermore, several of the papers used for the background research of this thesis have been published within the past year.

Among the newer blockchain technologies is the Hyperledger platform. Version 1.0 was released in March 2017, and version 1.1 in March 2018. This platform has great potential for developing a system such as the one presented in this thesis. However, rather than spending a lot of time learning a specific framework, the goal was rather to learn the blockchain functionality, and this was done by implementing a blockchain form scratch. In retrospect, this might not have resulted in the best possible system. However, it has given tremendous insight in how blockchains work and their abilities, and more importantly - their limitations.

The advantages of building the blockchain structure from scratch is that it can be formed exactly how the system specifications require it to be. Furthermore, the system can be implemented without transaction fees, which would be required e.g. on the Ethereum platform.

The disadvantages of not utilizing existing blockchain platforms is that it requires more extensive testing to ensure correct behavior, more maintenance, and more documentation. By using an existing blockchain platform, like Hyperledger Fabric, the development of the system would most likely be faster, seeing as the low-level modules are implemented, thoroughly tested, and ready for use. Hyperledger also has a built-in smart contract program in *chaincode*. The modular architecture of Hyperledger Fabric presents the ability to design the system just as required.

Consensus

As previously mentioned, the consensus module is not without flows, as became clear in the testing. Other issues regarding the module include the lack of protection against Byzantine nodes. It can be argued that in a consortium blockchain where nodes are validated, fault-tolerance is sufficient and the system does not need to be BFT. Furthermore, as such a system would be restricted to a limited physical area, it is quite likely that network participants are acquaintances in real life, thus reducing the risk of Byzantine nodes. Nonetheless, in the current implementation nodes are not part of the validation process, they simply require the IP address and port number of a node in the network. A brute force attack could quite easily access the network and establish itself as a leader by starting to send out *append entries* messages.

One of the big advantages of the RAFT protocol, apart from being very understandable and quite easy to implement, is that there are no possibilities for forks in the network, due to the strong consistency of the consensus protocol. Once a block is commited to the blockchain, it is commited by all nodes and no other block can be commited in its place. Another, and more important advantages, is that there is no need for any tokens or crypto currencies in the network. In contrast to the PoW protocol in the Bitcoin blockchain, which require enormous amounts energy to operate, the RAFT protocol is a lightweight protocol, that can run on normal processing capacity.

Network

In the current implementation of the network module, all nodes have an open connection to all other nodes in the system. This solution does not scale well when the network is extended. One possibility to solve this problem could be to limit each node to e.g. 5 connections. This requires that all messages are broadcasted and forwarded until they have reached all nodes in the network and could be achieved by numbering all messages.

On the other hand, the network protocol works very well. The *Twisted* library eased the development of the network communication, as the low level components of the protocol were abstracted away. This allowed for a well structured and modularized API.

Smart Contracts

Storage

As shown in the results, a block containing energy transactions from 4 nodes resulted in approximately 423 bytes. With a new block created every minutes, this will eventually produce a large sized blockchain. A solution to this could be to limit the blockchain horizon to 3 years, which is how long power companies are required to store readings [67]. Thus, after year 4, the first year worth of blocks will be removed from the blockchain and the genesis block rewritten to match the new first block of the blockchain.

9.5 Future Work

Current implementation stores blockchain and other logs locally on machine, a future improvement could be to store the data in the cloud to save space.

To save space, blocks containing transactions that are settled or smart contracts that are no longer valid can be deleted.

Make new users part of validation - to ensure true consortium. Current solution can be attacked through brute force, since the only requirement to join is to know the IP address and port number of an existing node on the network.

Automatic selection of who to initiate smart contract with for consumer based on pre-defined constraints

Only some nodes part of validation? and let these have open connections to each other, let remaining nodes have connections to at least one of the validation nodes.

Merkel trees for scalability. Is there a point though, since merkel trees are for time saving (?) and we are not iterating through blockchain to find previous transactions. Maybe usable in smart contract blockchain

Increase BFT by signing messages to prove authenticity. - Consensus: limit consensus nodes to only 5.

Automatic smart contract based on pre-set prices given by prosumer and consumer

Settlement - better algorithm - including taking electricity from batteries for better flow

Hardware

Following is a summary of the future work that should be carried out on the system, based on what was discussed in this section and in section 9.4.

- lolz

Chapter 10

Conclusion

To build such a system on top of existing blockchains such as Bitcoin or Ethereum, may result in a costly system, due to relatively large transactions fees and many, low-value transactions in the microgrid network. Ethereum, in addition, requires Ether to run applications/smart contracts on the EVM. Using the modular blockchain of Hyperledger might be a better idea, however - some cost?

The blockchain implemented in this thesis is able to run and process all transactions in the network at no additional cost.

Consortium - node ids are linked to identities - if a node tries to attack the blockchain, its identity will be known and actions may be taken thereafter.

Transparency - account owners can at any time review there account actions. Super user can see everything

Problem - all users can review all other users account activity through the blockchain ledger - however it is a rigorous task to read all account activity from the ledger. Thus, the application layer exist to make it easier to monitor account activity - and this is only available to the account owner.

Blockchain is still a fairly new technology with new advances at a rapid speed. They have already shown great potential to work in many different areas, including in an energy system, as showed in this thesis. Extensive testing and evaluation of possible implementation should be executed before it can run in the proposed system.

Appendices

Appendix A

Test data

Date	Consumed	Produced
21-05-18 00:00	0	-0.043
21-05-18 00:01	0	-0.169
21-05-18 00:02	0	-0.352
21-05-18 00:03	0	-0.492
21-05-18 00:04	0	-0.18
21-05-18 00:05	0	-0.274
21-05-18 00:06	0	-0.435
21-05-18 00:07	0	-0.175
21-05-18 00:08	0	-0.285
21-05-18 00:09	0	-0.473
21-05-18 00:10	0	-0.353
21-05-18 00:11	2.4225	-0.127
21-05-18 00:12	3.298	-0.053
21-05-18 00:13	3.309	-0.125
21-05-18 00:14	3.316	-0.049
21-05-18 00:15	3.31	-0.066
21-05-18 00:16	3.2985	-0.131
21-05-18 00:17	3.2925	-0.195
21-05-18 00:18	3.2925	-0.243

Figure A.1: Transaction data for node 274b2397-508c-419d-aa75-d0a909a80dd1

Date	Consumed	Produced
21-05-18 00:00	2.122	-0.496
21-05-18 00:01	4.714	-0.497
21-05-18 00:02	5.151	-0.212
21-05-18 00:03	5.147	-0.33
21-05-18 00:04	5.117	-0.129
21-05-18 00:05	5.083	-0.224
21-05-18 00:06	5.12	-0.019
21-05-18 00:07	5.105	-0.116
21-05-18 00:08	5.113	-0.157
21-05-18 00:09	5.125	-0.142
21-05-18 00:10	4.475	-0.053
21-05-18 00:11	2.129	-0.126
21-05-18 00:12	2.148	-0.16
21-05-18 00:13	2.151	-0.134
21-05-18 00:14	2.152	-0.289
21-05-18 00:15	2.154	-0.281
21-05-18 00:16	2.152	-0.332
21-05-18 00:17	2.151	-0.214
21-05-18 00:18	2.152	-0.299

Figure A.2: Transaction data for node 712b259d-3d24-431e-b4b8-e091b3a38ad6

Bibliography

[1] Investopedia Staff. “The collpas of Lehman Brorthers: A case study”. In: *Investioedia* (Dec. 2017). URL: https://www.investopedia.com/articles/economics/09/lehman-brothers-collapse.asp.

[2] Satoshi Nakamoto. *Bitcoin open source implementation of P2P currency.* URL: http://p2pfoundation.ning.com/forum/topics/bitcoin-open-source.

[3] Marco Iansiti and Karim R. Lakhani. “The Truth About Blockchain”. In: *Harvard Business Review* (Jan. 2017). URL: https://hbr.org/2017/01/the-truth-about-blockchain.

[4] M. Mihaylov et al. “NRGcoin: Virtual currency for trading of renewable energy in smart grids”. In: *11th International Conference on the European Energy Market (EEM14)*. 2014, pp. 1–6. DOI: 10.1109/EEM.2014.6861213.

[5] *Brooklyn Microgrid 101.* URL: http://brooklynmicrogrid.com/.

[6] Ernie Hayden. “Introduction to Microgrids”. In: (). URL: https://www.securicon.com/sites/default/files/Introduction%20to%20Microgrids%20-%20Securicon%20-%202013_1.pdf.

[7] *Microgrids, the self-healing solution.* URL: https://www.generalmicrogrids.com/about-microgrids.

[8] O.I. Konashevych. “Advantages and Current Issues of Blockchain Use in Microgrids”. In: *Electronic Modeling - Vol. 38, No. 2.* 2016, pp. 93–103. URL: http://dspace.nbuv.gov.ua/handle/123456789/101347.

[9] *How Microgrids Helped Weather Hurrican Sandy.* URL: https://www.greentechmedia.com/articles/read/how-microgrids-helped-weather-hurricane-sandy#gs.gO_LP24.

[10] ABB. *Introduction to Microgrids.* URL: http://new.abb.com/distributed-energy-microgrids/introduction-to-microgrids.

[11] Mary M Timney. *Power for the People: Protecting States’ Energy Policy Interests in an Era of Deregulation: Protecting States’ Energy Policy Interests in an Era of Deregulation.* Routledge, 2015. ISBN: 9781317462293.

[12] Janusz Bialek. “Tracing the flow of electricity”. In: *IEE Proceedings-Generation, Transmission and Distribution* 143.4 (1996), pp. 313–320.

[13] Satoshi Nakamoto. *Bitcoin: A peer-to-peer electronic cash system.* 2009. URL: http://bitcoin.org/bitcoin.pdf.

[14] Michael Nofer et al. "Blockchain". In: *Business & Information Systems Engineering* 59.3 (June 2017), pp. 183–187. ISSN: 1867-0202. DOI: 10.1007/s12599-017-0467-3.

[15] Vitalik Buterin. *On Public and Private Blockchains.* Blog. Aug. 2015. URL: https://blog.ethereum.org/2015/08/07/on-public-and-private-blockchains/.

[16] X. Xu et al. "A Taxonomy of Blockchain-Based Systems for Architecture Design". In: *2017 IEEE International Conference on Software Architecture (ICSA).* Apr. 2017, pp. 243–252. DOI: 10.1109/ICSA.2017.33.

[17] Z. Zheng et al. "An Overview of Blockchain Technology: Architecture, Consensus, and Future Trends". In: *2017 IEEE International Congress on Big Data (BigData Congress).* June 2017, pp. 557–564.

[18] Wenting Li et al. "Securing Proof-of-Stake Blockchain Protocols". In: *Data Privacy Management, Cryptocurrencies and Blockchain Technology.* Ed. by Joaquin Garcia-Alfaro et al. Cham: Springer International Publishing, 2017, pp. 297–315. ISBN: 978-3-319-67816-0.

[19] Leslie Lamport, Robert Shostak, and Marshall Pease. "The Byzantine Generals Problem". In: *ACM Trans. Program. Lang. Syst.* 4.3 (July 1982). ISSN: 0164-0925. DOI: 10.1145/357172.357176. URL: http://doi.acm.org/10.1145/357172.357176.

[20] Scott Driscoll. *How Bitcoin works under the hood.* URL: http://www.imponderablethings.com/2013/07/how-bitcoin-works-under-hood.html.

[21] K.J. O'Dwyer. "Bitcoin Mining and its Energy Footprint". In: *IET Conference Proceedings* (Jan. 2014), 280–285(5). URL: http://digital-library.theiet.org/content/conferences/10.1049/cp.2014.0699.

[22] *Bitcoin Energy Consumption Index.* URL: https://digiconomist.net/bitcoin-energy-consumption.

[23] Dr. Arati Baliga. *Understanding Blockchain Consensus Modles.* Tech. rep. Apr. 2017. URL: https://www.persistent.com/wp-content/uploads/2017/04/WP-Understanding-Blockchain-Consensus-Models.pdf.

[24] *Ethereum wiki - Proof of Stake FAQ.* URL: https://github.com/ethereum/wiki/wiki/Proof-of-Stake-FAQ.

[25] *Proof of Stake - The Rich get Richer...Less!* 2018. URL: https://steemit.com/crypto/@neoversion6/proof-of-stake-the-rich-get-richer-less.

[26] Gert Rammeloo. "The economics of the Proof of Stake consensus algorithm - Proof of Stake: an economic analysis". In: *Meduim* (2017). URL: https://medium.com/@gertrammeloo/the-economics-of-the-proof-of-stake-consensus-algorithm-e28adf63e9db.

[27] Diego Ongaro and John Ousterhout. "In Search of an Understandable Consensus Algorithm". In: *Proceedings of the 2014 USENIX Conference on USENIX*

Annual Technical Conference. USENIX Association, 2014, pp. 305–320. ISBN: 978-1-931971-10-2. URL: http://dl.acm.org/citation.cfm.
[28] Leslie Lamport. "Paxos Made Simple". In: 2001.
[29] Miguel Castro and Barbara Liskov. "Practical Byzantine Fault Tolerance and Proactive Recovery". In: *ACM Trans. Comput. Syst.* 20.4 (Nov. 2002), pp. 398–461. ISSN: 0734-2071. DOI: 10.1145/571637.571640. URL: http://doi.acm.org/10.1145/571637.571640.
[30] Linux Foundation. *About Hyperledger*. URL: https://www.hyperledger.org/about.
[31] *Hyperledger Fabric Ordering Service*. URL: https://github.com/hyperledger/fabric/blob/13447bf5ead693f07285ce63a1903c5d0d25f096/orderer/README.md.
[32] Amrutha Gayathri. "From marijuana to LSD, now illegal drugd delivered on your doorstep". In: *International Business Times* (June 2011).
[33] Vitalik Buterin. *Visions Part 1: The Value of Blochain Technology*. Blog. Apr. 2015. URL: https://blog.ethereum.org/2015/04/13/visions-part-1-the-value-of-blockchain-technology/.
[34] Alex Lielacher. *Sending Money? Why Not Do it with Bitcoin*. Dec. 2017. URL: https://wirexapp.com/use-bitcoin-send-receive-international-money-transfers/.
[35] World Bank Group. "Remittance Prices Worldwide". In: (Mar. 2017). URL: https://remittanceprices.worldbank.org/sites/default/files/rpw_report_march_2017.pdf.
[36] Steven Buchko. *How Long do Bitcoin TransactionsTake?* Dec. 2017. URL: https://coincentral.com/how-long-do-bitcoin-transfers-take/.
[37] Stan Higgins. "Bitcoin-Powered Crowdfunding App Lighthouse Has Launched". In: *Coindesk* (2015). URL: https://www.coindesk.com/bitcoin-powered-crowdfunding-app-lighthouse-launches-open-beta/.
[38] *Ethereum - Blockchain App Platform*. URL: https://www.ethereum.org/.
[39] Alyssa Hertig. "Who created Ethereum". In: *Conidesk* (Mar. 2017). URL: https://www.coindesk.com/information/who-created-ethereum/.
[40] Vitalik Buterin. *Ethereum White Paper*. Tech. rep. Ethereum Foundation, 2013. URL: https://github.com/ethereum/wiki/wiki/White-Paper.
[41] *What is Ethereum?* URL: http://www.ethdocs.org/en/latest/introduction/what-is-ethereum.html.
[42] *News by the people, for the people*. URL: https://dnn.media/.
[43] *Open Identity System for the Decentralized Web*. URL: https://uport.me.
[44] Linux Foundation. *Hyperledger Fabric*.
[45] Linux Foundation. *Industries*. URL: https://www.hyperledger.org/industries.
[46] *SWIFT's Blockchain Pilot For Bank-To-Bank Transfers Went Extremely Well*.
[47] Maciek Jedrzejczyk. *eVoting in Poland becomes a moonshot with blockchain*. Jan. 2018. URL: https://www.linkedin.com/pulse/evoting-poland-becomes-moonshot-blockchain-maciek-j%C4%99drzejczyk/?trackingId=hIoC1Jyjj0c58Ts6MwpEMA%3D%3Dtd%3E.

[48] *A peer-to-peer platform for efficient trade of electricity.* URL: https://www.nadgrid.com/.

[49] Sujha Sundarajan. "Japanese Shipping Giant, IBM to Trial Blockchain in Cross Border Trade". In: *Coindesk* (Dec. 2017). URL: https://www.coindesk.com/japanese-shipping-giant-ibm-to-trial-blockchain-in-cross-border-trade/.

[50] Claude R. Olsen. "Blokkjeder år fart på verdenshandelen". In: *Teknisk Ukebland* (Apr. 2018), pp. 76–81. ISSN: 0040-2354.

[51] Nick Szabo. "Formalizing and Securing Relationships on Public Networks". In: *First Monday* 2.9 (Sept. 1997). ISSN: 13960466.

[52] Nicola Atzei, Massimo Bartoletti, and Tiziana Cimoli. "A survey of attacks on Ethereum smart contracts (SoK)". In: *International Conference on Principles of Security and Trust*. Springer. 2017, pp. 164–186.

[53] *Electric Power Technical Whitpaper.* Tech. rep. Dec. 2017. URL: https://exergy.energy/wp-content/uploads/2017/12/Exergy-Whitepaper-v8.pdf.

[54] Clinton Nguyen. "Brooklyn's 'Microgrid' Did Its First Solar Energy Sale". In: *Motherboard, Vice* (Apr. 2016). URL: https://motherboard.vice.com/en_us/article/d7y7n7/transactive-grid-ethereum-brooklyn-microgrid.

[55] Urszula Papajak. "Can the Brooklyn Microgrid project revolutionize the energy marke?" In: *Medium* (Nov. 2017). URL: https://medium.com/thebeammagazine/can-the-brooklyn-microgrid-project-revolutionise-the-energy-market-ae2c13ec0341.

[56] James Basden and Michael Cottrell. "How Utilities Are Using Blockchain to Modernize the Grid". In: *Hardware Business Review* (2017). URL: https://hbr.org/2017/03/how-utilities-are-using-blockchain-to-modernize-the-grid.

[57] Esther Mengelkamp et al. "Designing microgrid energy markets: A case study: The Brooklyn Microgrid". In: *Applied Energy* 210 (2017), pp. 870 –880. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2017.06.054. URL: http://www.sciencedirect.com/science/article/pii/S030626191730805X.

[58] Coinstar. *NAD Grid - Thomas Sun - APAC Blockchain Conference 2018.* Youtube. Mar. 2018. URL: https://www.youtube.com/watch?v=euTqN3ZJE00.

[59] *How NAD Grid Work.* URL: https://nadgrid.com/.

[60] *Power Ledger.* URL: https://powerledger.io.

[61] *Power Ledger White Paper.* Tech. rep. 2018. URL: https://powerledger.io/media/Power-Ledger-Whitepaper-v8.pdf.

[62] *Python Software Foundation.* URL: https://www.python.org/.

[63] *Twisted Matrix Labs.* URL: https://twistedmatrix.com/trac/.

[64] *Flask - Web Development One Drop at a Time.* URL: http://flask.pocoo.org/docs/1.0/ (visited on 05/25/2018).

[65] *Pure-Python ECDSA.* URL: https://github.com/warner/python-ecdsa (visited on 05/25/2018).

[66] *hashlib - Secure hashes and message digests.* URL: https://docs.python.org/3/library/hashlib.html.

[67] 7. "Vil lagre dine strømdta i 10 år". In: *Teknisk Ukeblad* (2012). URL: https://www.tu.no/artikler/vil-lagre-dine-stromdata-i-ti-ar/235540 (visited on 05/30/2018).