Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Electric Power Engineering

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Blockchain Technology Implementation for Electric Vehicle Charging within the Smart Grid Architecture Model

Master's thesis in Energy and Environmental Engineering
Supervisor: Irina Oleinikova
June 2019

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Abstract

This thesis investigates the potential of implementing the novel blockchain technology as a tool in smart grids. Traditional energy systems are currently facing new challenges and undergoing a transition towards smarter and more complex energy systems. Energy and climate policy and interrelated trends are driving the power system towards smart grids. Smart grids integrate new solutions and services and are characterised by extensive utilisation of information and communication technologies (ICT). The Smart Grid Architecture Model (SGAM) is introduced as a framework to increase the understanding of smart grid concepts. The SGAM methodology is used as a standardised approach to developing the smart grid use case "electric vehicle charging". One of the focal points in smart grids is to fully integrate the growing electric vehicle fleet into the power system.

Blockchain technology is gaining attention in the energy sectors, as a promising tool in the increasingly complex system. The novel technology has the potential to transform operations and markets by reducing friction and redefining roles in a system. By analysing the blockchain technology characteristics, it is recognised the technology can support the energy transition, and contribute to the ICT needs of a decentralised and dynamic power system with consumers at heart.

The decentralised architecture of electric mobility, with multiple actors is as a promising application area for blockchain in smart grids. By considering the use case "electric vehicle charging" developed according to the SGAM methodology, functions and interactions involved are revealed. Here blockchain technology can be applied as an information technology to provide interoperable and innovative charging systems. Blockchain can reduce interaction and information frictions in a charging process while securing information and transactions. A specific application scenario is developed, where a blockchain-based system connects the actors and processes functions in electric vehicle charging. Additionally, the solution can integrate information flow for the provision of services to the power grid operation through demand response. The blockchain-based charging system is implemented on the Ethereum blockchain platform for proof of concept. The implementation and simulation prove a feasible solution by the use of smart contracts.

Sammendrag

Denne oppgaven undersøker potensialet for å implementere blokkjedeteknologi som et verktøy i smarte nett. De tradisjonelle energisystemene står for tiden overfor nye utfordringer og gjennomgår en overgang til smartere og mer komplekse energisystemer. Energi- og klimapolitikk og trender fører en utvikling av smarte nett. Smarte nett integrerer nye løsninger og tjenester, og er preget av en omfattende bruk av informasjons- og kommunikasjonsteknologi. Smart Grid Architecture Model (SGAM) er introdusert som et rammeverk i smarte nett for å øke forståelsen av nye og kompliserte konsepter. SGAM-metoden som en standardisert tilnærming brukes her for å utvikle brukstilfellet for lading av elbiler i smarte nett. Et av fokusområdene i smarte nett er å tilrettelegge for den voksende andelen elbiler som skal kobles til kraftnettet.

Blokkjedeteknologi får oppmerksomhet i energisektoren som et lovende verktøy i det stadig mer komplekse kraftsystemet. Den nye teknologien har potensialet for å påvirke driften av kraftsystemet og kraftmarkeder ved å redusere markedsfriksjoner og redefinere roller i systemer. Ved å analysere blokkjedeteknologis egenskaper, kan det ses at teknologien kan støtte endringer i energisystemet, og bidra til IKT behovene i et mer desentralisert og dynamisk kraftsystem, hvor forbukerne er i hovedfokus.

Den desentraliserte arkitekturen i elektrisk mobilitet er et lovende applikasjonsområde for blokkjeder i smarte nett. De involverte funskjonene og interaksjonene kan avdekkes ved å vurdere prosessen ved elbillading. Her kan blokkjedeteknologi brukes som informasjonsteknologi for sikre, interoperative og innovative ladesystemer. Blokkjeder kan redusere interaksjons- og informasjonsfriksjon i en ladeprosess. Et spesifikt applikasjonsscenario for blokkjedeteknologi for elbillading er utviklet, hvor systemet forbinder aktørene og funksjonene i ladeprosessen. I tillegg kan løsningen gi forbukerne mulighet til å bidra med tjenester for driften av kraftsystemet. Ladesystemet er implementert på en eksisterende blokkjedeplatform for å bekrefte gjennomførbarheten av applikasjonsscenarioet.

Preface

This master's thesis concludes my five year Master of Science (MSc) degree in Energy and Environmental Engineering at the Norwegian University of Science and Technology (NTNU). The thesis was completed in the spring semester of 2019, written under the supervision of Professor Irina Oleinikova at the Department of Electric Power Engineering at NTNU.

I would like to thank my supervisor, Professor Irina Oleinikova, for your guidance. I am grateful for your availability for discussions, and for giving me new insights. Further, I would like to acknowledge PhD candidate Sigurd Bjarghov for valuable help whenever needed.

The master's project has been frustrating at times, and I would like to extend my gratitude to my fellow students at the Department of Electric Power Engineering for support and enjoyable breaks throughout this year.

Finally, I would like to thank my friends at Energy and Environmental Engineering at NTNU. I am forever grateful for the five wonderful years we have had together in Trondheim.

Trondheim, June 2019
Mina Bergerøy Ryssdal

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List of Abbreviations

ACER	Agency for the Cooperation of Energy Regulators
BRP	Balancing responsible party
CEN	The European Committee for Standardization
CENELEC	The European Committee for Electrotechnical Standardization
CH	Clearing house
CSO	Charging station operator
dApps	Decentralised applications
DER	Distributed energy resource
DG	Distributed generation
DLT	Distributed ledger technology
DSO	Distribution system operator
EEA	European Economic Area
E-mobility	Electric mobility
EMSP	Electric mobility service provider
ENTSO-E	European Network for Transmission System Operators for Electricity
ESR	Electric supply retailer
EV	Electric vehicle
EVM	Ethereum virtual machine
EVSE	Electric vehicle supply equipment
EVU	Electric vehicle user
GHG	Greenhouse gas
IEC	International Electrotechnical Commission
ICT	Information and communications technology
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization
LEM	Local energy market
NVE	The Norwegian Water Resources and Energy Directorate
PV	Photovoltaics
RES	Renewable energy sources
SCADA	Supervisory Control and Data Acquisition

SGAM	Smart Grid Architecture Model
SOC	State of charge
TSO	Transmission system operator
V2G	Vehicle to grid

Introduction

Motivation

Traditional energy systems are currently undergoing a transition to smarter systems, due to environmental concerns, technological development and market liberalisation [5]. Energy and climate policy are driving the achievement of a low carbon system, increasing the penetration of renewable energy sources (RES) [6]. The consumer is in the centre of European energy and climate policy, where the aim is to empower and protect the energy consumer [7]. The end-users require better information, more choice and an option to participate in energy markets, e.g. as producers. Additionally, there is an adoption of distributed generation (DG) and electric vehicles (EV) that challenge traditional centralised control. Consequently, the power system is experiencing a change to a more decentralised system. The energy sector has to respond to the challenges of creating a fully internal market, integrating the increasing share of intermittent RES and managing the complex interactions between actors. The interrelated factors are diving the electrical power system towards smarter and more complex systems.

Smart grid concepts emerge to further encourage and facilitate for the energy transition [8]. Smart grids integrate new technology and actors in the system while optimising power and economic flows. To achieve these goals, the system highly depends on information and communication technologies (ICT) and new market design and business models. New value propositions are introduced to lower bills and environmental impact while improving social outcomes and ensure reliability, safety and quality of service. Innovation could change the operation of the markets by providing needed local focus and flexibility, and help consumers better engage and ensure they are treated fairly [2]. The use of non-traditional business models requires remodelling of energy markets and regulatory framework and the emergence of new ICT solutions. The initiatives have to be further developed to achieve the interrelated goals in Europe's climate and energy policy and transform energy markets and deliver desired outcomes for the consumers.

Blockchain technology is lately gaining attention from the electrical energy sector as a promising ICT in smart grids [9]. Blockchain is best known for its use in the financial service sector with cryptocurrencies such as Bitcoin [10]. Nevertheless, Blockchain can be a tool in the increasingly complex power system, where the decentralised architecture can put the consumer at the heart of the system. The novel technology has potential to transform operations and markets by reducing friction and redefining roles in a system [11]. Application of blockchain technology in electric mobility is possible transformative use of blockchain technology in the power system, contributing to further integration of electric vehicles into the power system, as part of the energy policy targets [9].

Research scope and objectives

This thesis investigates and demonstrates the implementation of blockchain technology in electric vehicle charging in smart grids. The Smart Grid Architecture Model (SGAM) methodology is used to develop and analyse the smart grid solution in a standardised manner [3]. The SGAM framework contributes to an analysis of where blockchain can be applied as a tool in the use case, by revealing actors, interactions and functions.

The objectives of the work are as follows:

1. Develop the smart grid use case ”electric vehicle charging” according to the SGAM methodology.
2. Analyse potential for applying blockchain as a tool in smart grids, in particular for functions in the ”electric vehicle charging” use case.
3. Develop a specific application scenario for blockchain in electric mobility in smart grids and perform a proof of concept by implementing the system on a blokchain platform.

The thesis contributes to the overall goal of energy policy by achieving the aims of this research. The blockchain technology implementation is proposed as an approach for the challenges in the future power system while putting consumers at the heart of the system. The smart grid concept of electric vehicle charging is developed according to the standardised SGAM methodology, which is used to discover underlying ICT requirements. Furthermore, the novel technology of blockchain is analysed and implemented to investigate the potential as a tool in future smart grids, by empowering consumers and enabling services and new business models in the power system. The Smart Grid Architecture Model (SGAM) methodology is proposed as an approach to analysing the ICT framework in a use case, and blockchain interaction in smart grids is demonstrated using SGAM. Correct implementation of the novel technology is crucial to enable the key benefits of blockchain and ensure a beneficial application in smart grid. This is considered in this work by performing a functional analysis on where the blockchain can be implemented. However, blockchain technology is not compared to other potential solutions and design variations of the blockchain protocol for implementation are not considered.

Thesis structure

The thesis is structured as follows:

Chapter 1, *Background - Towards smart grids*, explains the transition of the power system to smart grids. It introduces the traditional electrical power system and electricity markets and drivers for change through energy policy targets and trends and presents the concept of smart grids with its characteristics and requirements.

Chapter 2, *Smart Grid Architecture Model methodology*, explains the SGAM methodology, including the SGAM framework as a reference architecture, and a use case methodology for presenting smart grid use cases.

Chapter 3, *Blockchain technology*, provides an overview of blockchain technology, with its architecture and features, and discuss blockchain applications in smart grids, including presenting best practices.

Chapter 4, *Electric vehicles in smart grids*, presents the use case "electric vehicle charging" according to the SGAM methodology. Electric mobility in smart grids, regarding its role in power system operation and requirements of the EV users, is first introduced. The developed use case is then described, including actors, functions and interactions.

Chapter 5, *Blockchain in electric vehicle charging*, analyses the application of blockchain in electric vehicle charging by considering its potential contributions in the smart grid use case.

Chapter 6, *Application scenario and proof of concept*, proposes an application scenario of blockchain technology as a tool in electric vehicle charging. Additionally, an implementation of a blockchain-bases system is created on a blockchain platform for a proof of concept of the technical feasibility.

Chapter 7, *Conclusions*, draws the main conclusions on blockchain technology as a tool in smart grids, specifically on the application in electric vehicle charging. Finally, further work is proposed.

Remark: The thesis builds on the specialisation project by the same author, and as such, there is usage of the content therefrom in Chapter 1, Chapter 2 and Chapter 3.

Chapter 1

Background: Towards smart grids

The energy system is currently developing towards smarter energy system, which is challenging the operation of the electrical power system. This Chapter provides the relevant background information on the current and future power system, to highlight the need for use case development and new ICT solutions. It explains the transition from the traditional power system structure towards smart grids, including the driving factors for change, and introduces the concept of smart grids.

1.1 Power system structure and roles

The power system is the interconnected physical system for generation and transportation of electrical energy. It is a complex network of electrical components that has to be in constant balance. The actors, operation, and markets vary in different countries. In many countries, the power sector faced a restructuring that began in the 80-90s [12]. The reorganisation of the electrical supply industry was started to increase competition, efficiency and reduce costs. The system was deregulated by liberalising the electricity markets and unbundling of the generation sector.

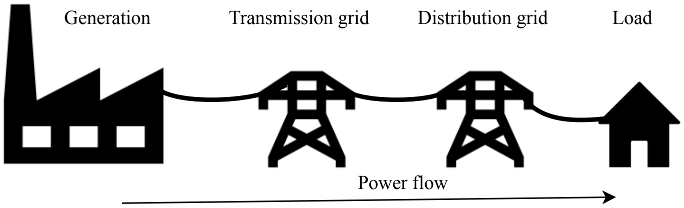


Figure 1.1: Centralised power system structure.

The current grid is designed for centralised power generation with unidirectional power flow, as illustrated in Figure 1.1. Power is primarily generated by centralised production with large power plants run by fossil fuels, nuclear and hydro [13]. These are firm-capacity generators, meaning they can be switched on and off on demand. The power generated is supplied to the load by the electrical grid. The electrical grid can is separated into the transmission and the distribution grid. The transmission grid transports electrical energy from large power plants with high voltage. The power is distributed locally to the load on the distribution grid.

Grid companies build, operate and maintain the physical grid infrastructure. The grid companies are responsible for connecting customers, provide sufficient network capacity and upgrade the grid if necessary. For the transmission grid, the grid operation is often combined with system operation done by the transmission system operator (TSO). Statnett is the only TSO in Norway and is publicly owned [14]. The system operator is responsible for the security and quality of supply by keeping the power system in balance. The distribution network operator operates the distribution grid and is often referred to as the distribution system operator (DSO). The regulator in the power system is responsible for the system and grid operators. The Norwegian Water Resources and Energy Directorate (NVE) has the regulatory role in Norway [15]. The regulator has to make sure that laws and regulations are followed in the electricity market and ensures market efficiency.

1.1.1 Electricity markets

The electricity market is an organised market place established for efficient power exchange The market operator is managing the electricity market, and the Nordic power exchange is operated by Nord Pool, which was the world's first international power exchange [16]. Through the agreement on the European Economic Area (EEA), Norway is a part of the EU's internal energy market. Today's electricity market has a centralised structure and is divided into the wholesale market and the retail market. Large industrial end-user often purchased directly from the wholesale market, while the smaller end-users buy from suppliers on the retail market. Electricity can also be traded directly between parties by bilateral contracts with pre-determined specified criteria. In the wholesale market, the price is set by matching supply and demand. The settlement makes the wholesale market a crucial mechanism in balancing the power system. The wholesale market consists of the day-ahead market, the intraday market and the balancing market.

The day-ahead market is the primary market where large volumes are traded for the following day. The day-ahead market is auction-based, where the participants make bids on purchase and sale, the price is set by supply-demand balance, and contracts are made for each hour of the following day. The intraday market opens for continuous trading up to one hour before the operation hour and enables the participants to adjust the trading to get closer to balance.

The actual power consumption or generation should be equal to the contracted volume. Any imbalances have to be settled by the TSO. Imbalances from the schedule from the day-ahead and intraday market are handled by the balancing market. The balancing market is used to regulate consumption or production up or down to maintain frequency balance. Imbalances occur due to unforeseen fluctuations within the operation hour. Participants in the wholesale market must have a balance agreement with the TSO, either directly or through a representative. The balancing responsible party (BRP) has to aim for real-time compliance with the schedule and is financially responsible for imbalances. In the liberalised conditions, TSO is responsible for the balancing and security of supply of the power system. Ancillary services are utilised for this by the TSO. Ancillary services are essential approaches to provide quality of supply and include a variety of services beyond generation and transmission.

To provide sustainable and secure system operation and competitive electricity markets, The European Network for Transmission System Operators for Electricity (ENTSO-E) and the Agency for the Cooperation of Energy Regulators (ACER) have created network codes as legally binding regulations [1]. The network codes have to be adopted to achieve Europe's long term climate and energy policy goals. The structure of the network codes is presented in Table 1.1.

Grid connection	**System operation**	**Market guidelines**
Demand connection code	Emergency and restoration	Electricity balancing
Requirements for generators	System operations	Forward capacity allocation
High voltage direct current connections		Capacity allocation and congestion management

Table 1.1: The network code families [1].

It is recognised that recently there has been a set of the new market design requirements and initiatives in the electricity sector with new entrants to the energy markets, such as flexibility provision, and some of them are using or require new and non-traditional business models. These opportunities in the electricity markets can be considered as necessary changes across the world, which will contribute to the development of the European internal energy market.

1.2 Drivers for change

The traditional energy sector is facing new challenges due to further market liberalisation and environmental concerns. A large number of converging factors are driving the energy sector towards smarter and more complex systems. It is motivated by political, regulatory, economic, societal and technical factors.

The development and deployment of smart energy systems initiatives are linked with the central commitment to achieve the goals contained in climate and energy policy. According to the Ministry of Petroleum and Energy, the main priorities in the Norwegian energy policy are improving security of supply, successful development of renewable energy, more efficient and climate-friendly energy use and value creation based on Norway's renewable energy resources [17]. The European Union has ambitious plans for the transformation of the energy sector, namely the Energy Union. The objectives of the Energy Union are on energy security, solidarity and trust, a fully integrated European energy market, energy efficiency, decarbonising the economy, and research, innovation and competitiveness [5].

Low carbon economy

With the Paris Agreement from 2015, 195 countries aim to reduce the impact of climate change. The overall goal is to limit global warming to less than 2 degrees compared to pre-industrial temperature [18]. In the "2030 climate and energy framework" from the European Union, the targets are ambitious with at least 40% cuts in greenhouse gas emissions, 27% share for renewable energy and 27% improvement in energy efficiency by 2030 [19]. EU also has a long term-strategy towards a low-carbon economy and a goal of reducing the emissions by 80-95% by 2050 compared to 1990 levels [6]. Norway has committed to reducing the global greenhouse gas (GHG) emissions for the 2030 targets and is collaborating with EU for the long-term strategy towards a climate-neutral economy [20].

Due to RES and GHG targets, the electricity generation mix is expected to change from a thermal dominated production. The share of RES is already rapidly increasing in the EU and the rest of the world and is expected to continue to grow to meet the targets. In 2017, over two-thirds of the total installed electricity capacity in the world was from renewable generation installations [21]. Wind and solar power are emerging in Norway, with wind power as the fastest growing source. In an analysis by Statnett, it is predicted that the wind power capacity in Norway will be doubled by 2030 [22]. However, hydropower is expected to continue to dominate in Norway, with 95% of the electricity production [23]. The general shift from thermal power plants to solar and wind energy reduces pollution from the energy sector. Nevertheless, it introduces new issues as the new generation technologies are more inflexible and variable.

Supply from intermittent RES brings additional uncertainty to the forecasted supply-demand power balance. Solar photovoltaics (PV) and wind power plants are variable since they only generate when there are wind and sun. On the contrary, fossil fuel generation is adjustable. The dependence on variable circumstances on generation can threaten the adequacy in the power system with significant penetration of stochastic RES. It can also result in curtailment if generation conditions are good and production exceeds demand. Furthermore, the power system security is affected by the variability and lack of flexibility in solar and wind power plants. The solar power is fluctuating due to weather change, causing power quality and voltage problems [24]. Conventional power plants deliver inertial response to the system which is crucial to the fast balancing in case of disturbances, while the increasing share of partly uncontrollable RES adds more variability to frequency balancing and stability issues [25].

The share of electricity in the final energy consumption is expected to increase to 28 % in Europe by 2050 [26]. Electrification is considered a crucial step in reducing emissions when the generation is shifted from fossil fuels. The electricity demand in the residential sector is growing due to an increase in electric heating, appliances and mobility. Electrification of the transport system plays a vital role in the reduction of emission, as the transport sector is responsible for almost a quarter of the GHG emissions in Europe [27]. With continued technological development and ambitious targets and policies, there can be 220 million electric vehicles on the road by 2030 [28]. The impact of electric vehicles is of particular importance in the Norwegian power system. Norway is world-leading in the adoption of electric vehicles with a market share of 49% in 2018 [29] and a goal that all new cars sold by 2025 will be zero-emission vehicles [30].

Decentralisation

Today's electricity grid is, as explained, designed for centralised generation from large power plants that are fed into the transmission grid with one-way distribution to the passive consumers on the low voltage side. The introduced renewable power plants are commonly installed at new geographical areas introducing generation to new parts of the grid. The installed renewable energy is often smaller production plants [31]. Furthermore, the plants are often decentralised and connected at the distribution level. The generation that is grid connected at the distribution level is called distributed generation or distributed energy resources (DER) and can include energy storage solutions [32]. This reduces transmission losses as the energy production is closer to where it is consumed. The grid-connected generation in the distribution network distinguishes from the traditional utilisation of the grid. The two-way power flow increases the complexity in the distribution grid, which deviates from the traditional passive distribution system. The traditionally passive and inflexible consumers are also starting to engage in the production of electricity due to technology development and price reduction in RES and DG. The term ”prosumers” is used for a customer that also produces electricity by DG, often accomplished by rooftop solar PV. To avoid curtailment and ensure additional income, the prosumers want to sell excess electricity to the grid.

Empower consumers

The power system is shifting from being centralised, towards a more decentralised system with an increased focus on the customer, as illustrated in Figure 1.2. Consumers are at the

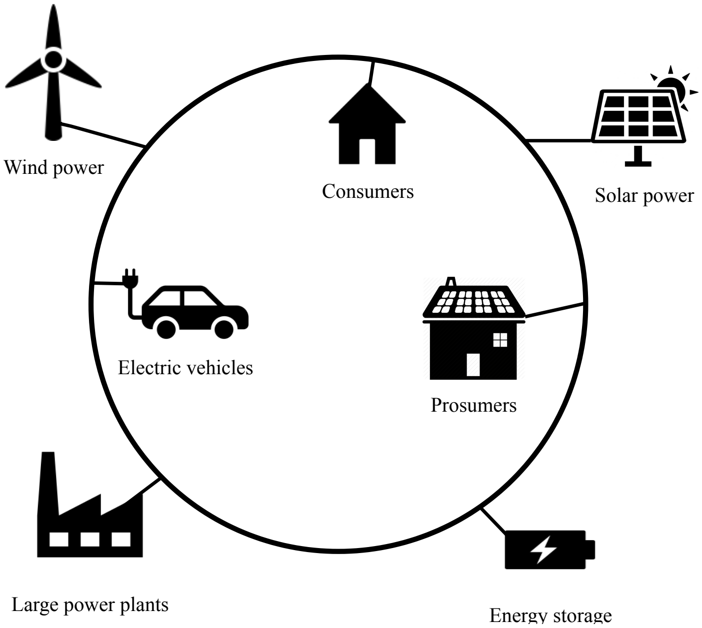


Figure 1.2: Decentralised, customer centred power system.

centre of the EU's energy policy. Considering the lack of consumer engagement and trust, there is a need for updated market design and models empowering end-consumer, including allowing participation of demand response solutions to all electricity markets and services. The importance of empowering and protecting energy consumers is a priority area in a fully integrated internal energy market. The "Clean energy for all Europeans" package from 2016 is a legislative framework that will help accelerate the goal of providing a fair deal for consumers [7]. The aim is to offer the consumer better information, more choice, lower costs, and protection. To empower the consumer, it is important to ensure the right tools with the right data to the right needs [33].

1.3 Smart grids

The mentioned changes have already started, but further facilitation and adaption to enable the transition to continue are required. The electrical power system has to respond to the interrelated challenges of creating a fully internal market, integrating the increasing RES and managing the complex interactions between actors in the system. It impacts and challenges the traditional operation and demands new, flexible solutions to ensure a reliable, secure and cost-efficient power system [34] [35]. Here smart grid concepts emerge to optimise both economic and power flows. Smart grids are the future electricity grids that consider the needs of the power system intelligently. EU, The European Committee for Standardization (CEN) and The European Committee for Electrotechnical Standardization (CENELEC) and International Electrotechnical Commission (IEC) define smart grid as the following [36] [8] [37].

> *"A smart grid is an electricity network that can integrate in a cost-efficient manner the behaviour and actions of all users connected to it, including generators, consumers and those that both generate and consume, in order to ensure economically efficient, sustainable power system with high levels of quality and security of supply and safety."*

The smart grid uses digital and other advanced technologies to monitor and control the electricity system [33]. In general, the system requires more decentralised control to handle local problems and focus [34]. The importance of the DSO role is expected to increase. The DSO will operate the distribution system, facilitate for remodelled markets and provide local solutions.

The characteristics of smart grids are highly dependent on extensive integration and use of information and communication technologies (ICT). In a more complex power system, the formerly passive end user wants the opportunity to make choices and participate. Greater information is demanded on own consumption, the generation source for the electricity and choice of supply. By the beginning of 2019, all electricity customers in Norway will have smart meters installed [38]. The smart meter roll-out is important in enabling new energy-related services. Smart meters provide real-time information about electricity consumption and prices. Secure sharing of data opens up for consumer engagement and new system operation opportunities, as the consumers can make informed choices and participate in energy markets. This includes providing flexibility by demand response.

In addition to the dependence on ICT, smart grids are characterised by new market design. The time resolution of the wholesale market is not suited to react to the increasing fluctuations. According to the EU, the electricity markets need to be remodelled to further encourage RES investments, utilisation of DER and consumer engagement [39]. The updated markets and new products create new services and business opportunities with the entry of new market roles and players. Engaged consumers and distributed resources can support the DSO in operation of the distribution grid and by market participation [40]. An overview of potential services and non-traditional business models in the energy markets is provided in Table 1.2.

Local services	**Bundled services**	**Customer participation**
Community	Energy service companies	Peer-to-peer
Municipal	Multi-service providers	Demand side flexibility
Housing association	Market services	Prosumers
		Next generation intermediaries

Table 1.2: Non-traditional business models in energy markets [2].

To achieve the interrelated goals in Europe's climate and energy policy, smart grid initiatives have to be further developed to transform energy markets and deliver desirable outcomes for the consumers.

Chapter 2

Smart Grid Architecture Model methodology

To realise the smart grid concepts, the power system has to integrate new stakeholders, services and in particular ICT, and respond to a dynamic interaction between multiple actors and technologies as discussed in Chapter 1. The smart grid raises the overall complexity in the power system and can be considered a system of interoperable systems, of which the power grid is one subsystem. This interoperability framework entails the capability of two or more networks, systems, devices, applications or components to exchange and readily use information in a secure and effective manner with no inconvenience to the user. However, a lack of understanding of smart grid issues and limited structure in the development of new use cases to ensure interoperability are key challenges in the complex system [41]. Structured frameworks are needed to support concept and strategy development, for better understanding and evaluation and to obtain standardised solutions. The Smart Grid Coordination Group of CEN-CENELEC propose a smart grid reference architecture to achieve interoperability with the use of use cases [3]. Based on the EU Mandate M/490, the Smart Grid Architecture Model (SGAM) and the IEC 62559 Use Case Methodology were developed [42]. The SGAM methodology can be used for developing and assessing smart grid use cases [43]. In the following of this chapter, the SGAM framework and the use case methodology are presented.

2.1 SGAM framework

The SGAM framework offers an architectural approach for design, development and validation of smart grid use cases. The Smart Grid Architecture Model is used as a standardised solution to obtain a common and interdisciplinary understanding of functionalities and interoperability of various power system domains, business divisions and authorities. The structure of the

SGAM can be seen in Figure 2.1.

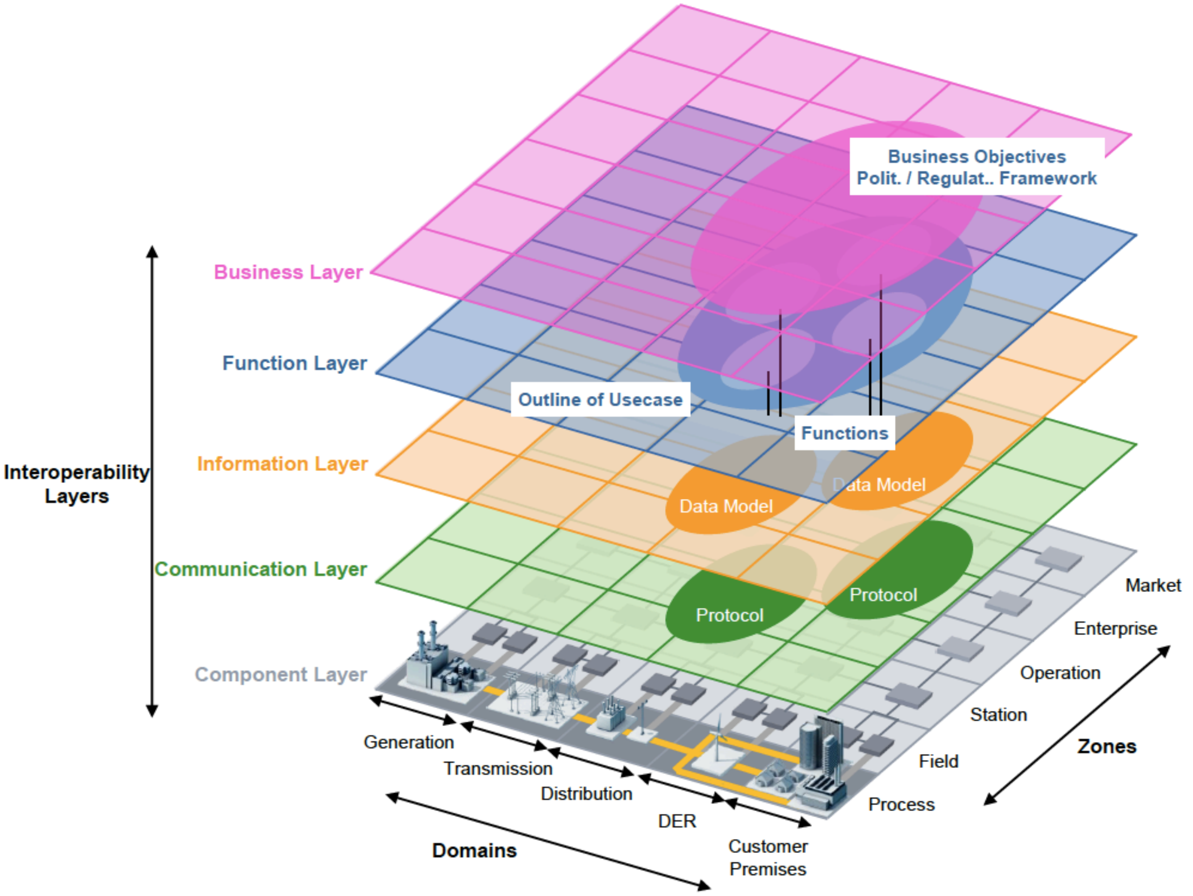


Figure 2.1: The Smart Grid Architecture Model [3].

Interoperability is crucial for the interaction between the systems within smart grids, and the SGAM presents five interoperability layers: The domains include the following:

- **The business layer** represents information with a business view and maps regulation and economic structures.
- **The function layer** describes functions and services including their relationships.
- **The information layer** represents information objects and the underlying data models.
- **The communication layer** describes protocols and standards used for communication between components
- **The component layer** cover technical and physical components, including ICT devices and the power grid.

The domains include the electrical energy conversion chain, and consist of generation (from large power plants), transmission, distribution, DER and customer premises (including all types of consumers and prosumers). The domains in the model are separated into different zones describing the power system management in hierarchical order after distance to the power grid. The first zone, the process zone includes physical energy conversion and corresponding equipment. The remaining five zones are related to information management. The field zone includes equipment and devices to monitor and control the process of the power system on a specific level, while the station zone represents the aggregated level, including local Supervisory Control and Data Acquisition (SCADA) systems. The operation zone includes power system management systems in the respective domain, e.g. distributed management systems. The enterprise zone represents commercial and organisational processes and services, e.g. management of customers, while the market zone provides market operations, such as energy trading. SGAM's three-dimensional architecture proposes a generic smart grid model that allows for graphical representation of smart grid use cases.

2.2 Use case methodology

As more and more use cases for smart grids are developed, coherent descriptions of use cases become necessary. The use case concept can be used in the smart grids to decompose the system of systems [42]. In this context, the standard IEC/PAS 62559 was developed, providing a standard methodology for use cases in smart grids. The methodology creates a structured way to describe smart grid functionality and identify actors and requirements.

The use case method origins from software engineering for requirements analysis to obtain a common understanding of a system. A use case describes the functionalities of a system, in order to to achieve a particular goal. The description of the use case focus on what the use case does, rather than how it is done. It contains a sequence of actions within a system and interactions between the system and the actors relevant to reach the objective of the use case. The actors are entities that are involved in the use case. An actor can, for instance, be a person, a device or an organisation. Within a use case, an actor assumes a specific role or a set of roles [44]. The IEC 62559 Use Case Methodology provides a template for describing use cases in the context of smart grids [42]. A basic/short version of the use case template includes a description of the use case, including the involved actors and use case diagrams.

When a use case is developed, the SGAM can be used to model the use case, by mapping the actors, devices and functions in the smart grid layers. To support smart grid deployment, use cases in smart grid is described and further visualised in the Smart Grid Architecture Model to describe system structure, requirements and interactions [40] [45] [46] [47]. The approach is proposed for the evaluation of smart grid concepts where blockchain technology can be implemented as an ICT and a tool for empowering the consumer in the increasingly complex power system.

Chapter 3

Blockchain technology

Initially, the blockchain technology became known due to its use in the financial service sector as the technology behind cryptocurrencies. Cryptocurrencies, such as Bitcoin, are electronic cash systems for money transactions [10]. However, blockchain technology is gaining interest in multiple sectors. It is anticipated that blockchain technology has the potential to transform operations and markets by reducing friction and redefining roles [11]. Researchers from various institutions and industry sectors are investigating the potential of the technology, and countries are paying particular attention to the development and application of blockchains [48]. The complexity in the power system is increasing, creating new ICT requirements, as explored in Chapter 1, where blockchain technology can be a tool.

This Chapter provides an overview of blockchain technology and an introduction to the application of blockchain in the power system and for smart grids. Blockchain is first described with its relevant principles and features, before application scenarios and practices of blockchain in smart grids are presented.

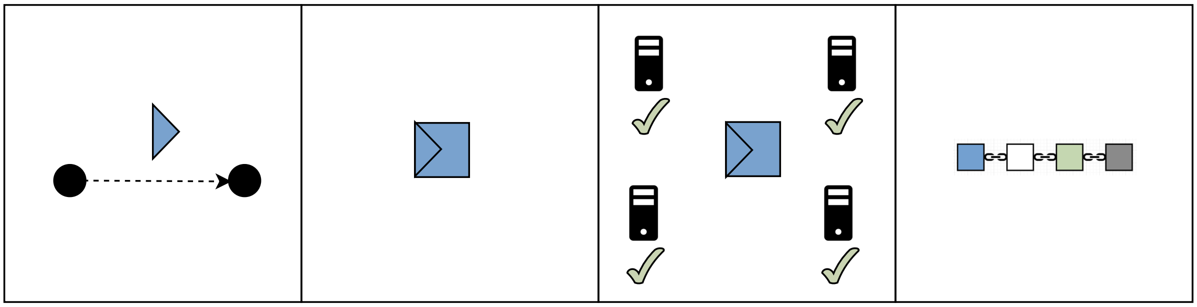
3.1 Blockchain architecture

Blockchain is a technology for exchanging of information between nodes in a network, where the nodes are the participants in the blockchain-based system. The blockchain operates on a network creating a decentralised, distributed architecture where a peer-to-peer connection supports interaction between the nodes. The blockchain technology can be described in a two-layer architecture, consisting of the protocol layer and the application layer, where the protocol layer sets the rules and basis for the technology, while the application layer describes the functions built on top of the protocol layer, creating applications.

3.1.1 Protocol layer

Blockchain technology is categorised as a distributed ledger technology (DLT). According to [49] , DLTs provide a decentralised concurrency control mechanism while maintaining consensus on shared facts where trust is embedded in the technology using cryptography. The shared facts are called transactions, which are information exchanged between nodes on the blockchain. Data recorded and exchanged for a monetary transaction on the Bitcoin blockchain include the amount transferred and metadata on the address of the sender and the receiver.

The blockchain technology uses decentralised consensus mechanisms and cryptography for secure and validated information flow. The blockchain's consensus algorithms and cryptographic measures are not described in depth, as it is beyond the scope of the work. A transaction is confirmed by a digital signature from the sender using a private key. The digital signature is created using an asymmetric cryptography, which makes it possible to verify the authenticity of the signature without the ability to tamper the transaction. The data from transactions are stored on "blocks", and each block contains a set of transactions. When a new block is created, it is distributed to multiple nodes, which validates the transactions, as illustrated in Figure 3.1.



1. Transaction requested

2. Transactions are combined to create a block

3. The nodes verify the block of transactions

4. The block is added to the chain

Figure 3.1: Validation of transactions on blockchain [4].

The blockchain technology has trust incorporated in the mathematics of the network. The technology relies on cryptographic proof and consensus algorithms for validation, which puts trust in the network instead of a central third-party institution. This removes the need for a central authority to record and verify transactions, in addition to the removal of centralised storage. The validation is to assure that all nodes agree on the legitimacy of a transaction and that it is added to the blockchain. The validation is done by implementing distributed consensus algorithms. One common method to reach consensus is the proof-of-work concept introduced by Satoshi Nakamoto [10]. The newest block is added to the ledger when it has been validated, as seen in Figure 3.1.

The blocks are put chronologically on a linked list or ledger. The blockchain is append-only, and changes, after a block is added, would create inconsistencies as the blocks are linked and encrypted using a Merkle tree data structure [11]. Each block includes information about the previous block which creates a pointer to the block and by that the "chain" in the blockchain. This makes the blockchain a *"continuously growing digital register of transactions"* [50]. In contrast to a traditional database solution, the data from the transactions in the system are not stored in a centralised unit. The whole blockchain is distributed and stored locally at each node in the network, hence the distributed ledger, as illustrated in Figure 3.2.

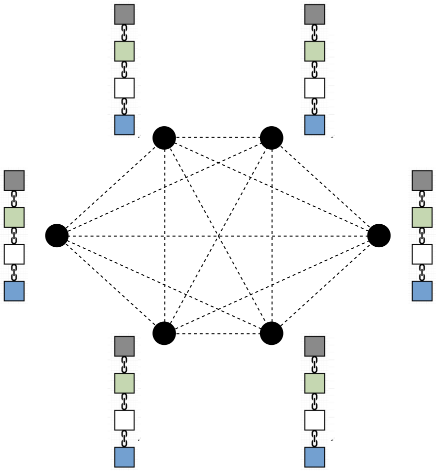


Figure 3.2: The blockchain distributed to the nodes in the decentralised network.

3.1.2 Application layer

Accordingly, the protocol layer of blockchain technology consists of transaction records, consensus rules and decentralised system created by distributed ledgers, cryptography and network of nodes. Applications that utilise the decentralised and secure architecture of the blockchain protocol can be developed . Cryptocurrencies, such as Bitcoin, are applications on blockchains, but the blockchain technology has application potential beyond digital tokens.

The blockchain environment Ethereum lead the introduction of the functionality of including smart contracts on blockchains. The smart contracts advance the potential of adding applications on top of the blockchain protocol [51], which are called decentralised applications (dApps). Decentralised applications can be built on already existing blockchains, such as Ethereum where thousands of dApps are developed. Consequently, it is not necessary to create a new blockchain for every new blockchain application. The applications use smart contracts as the logical back-end of the application to support more complex services. Smart contracts create automated transactions when certain rules are met. The rules or conditions are the terms of agreement of the contract. In the blockchain technology, smart contracts are programs that are self-executing when the specified conditions are obtained. Each smart contract in the system has its functionality and rules. When the contracts are getting information as input, the rules agreed upon are considered and the transaction enforced if the rules are met. As the smart contract is built on the blockchain, once a transaction is performed due to a contract it cannot be reversed.

When implementing an application of blockchain technology, the features of the blockchain technology have to be considered for assessing the fit and implementation of a blockchain application.

3.2 Technology features

3.2.1 Key qualities

The architecture of the blockchain technology creates beneficial features for application. The key qualities can be summarised as follows.

- **Decentralised:** Without the central authority to perform a transaction or enforce a contract, blockchain facilities direct and intermediate exchange between peers (peer-to-peer) in the network. The transactions get faster and cheaper without a third-party as unnecessary friction, and fares from going through a central unit can be avoided. This makes blockchain suitable for decentralised microtransactions integrating independent actors in energy markets. The decentralised nature and use of cryptography put the trust in the network itself, which ensures equal treatment of the nodes. The technology provides near real-time settlement of transactions, which are self-executing. Rapid settlement enhances the market's ability to contribute to real-time balancing by responding quicker to fluctuations.
- **Secure:** Smart contracts can be used to provide secure and instant monetary and contractual transactions following established rules. The instant payment ensures financial settlement between participants. Since the blockchain is validated and persistent it makes an irreversible and nearly tamper-proof log of transaction. When multiple nodes have the information stored, it reduces the risk of technical failure, corruption and cyber-attacks as a single point of failure is avoided. Inconsistencies will be detected due to the replication and distribution of the blockchain to multiple nodes, creating identical copies. Increased cybersecurity risk follows the growing implementation of smart devices. Blockchain can reduce the vulnerability for fraud and attacks, with secure networks and transparency.
- **Transparent:** All the participant in the system has access to the records due to the distributed log of transactions. The parties involved consequently have equal insight into information flow, decisions and changes. The transaction history is traceable and immutable, and the movement and origin of what is transacted can be confirmed.

3.2.2 Permissions

In addition to mentioned Bitcoin and Ethereum, there exist other blockchain protocols with various characteristics. An essential aspect for blockchain design is the degree of accessibility, in which blockchains can be categorised into three different types: public blockchains, consortium blockchains and private blockchains [52]. Cryptocurrencies such as Bitcoin are public blockchains, where everyone is allowed to join the system as a node. A public blockchain is considered fully decentralised where everyone has the same rights to read the information and contribute to the system, creating transparency [53]. However, this does not need to be the case, hence consortium and private blockchains. For these blockchain types, the transaction reading rights can be governed, and either be open or restricted. In a consortium blockchain, the consensus process is controlled by specified nodes. A private blockchain requires permission to participate, and the management and write access is centralised.

3.2.3 Challenges

The blockchain technology is an immature technology and is consequently facing challenges. The two primary issues with the current blockchain technology are scalability and privacy [54].

Scalability
Scalability includes the capability of processing complex transactions energy efficiently, fast and cheap in a large system. The time delay and the number of transactions possible are of importance for blockchain applications. The scalability of blockchain systems is studied in [55], where the Ethereum blockchain platform successfully processed a local energy market with clearing every fifth minute between 600 participants. Nevertheless, further research needs to be done on blockchain technology's ability to support complex computations for larger systems and rapid trading frequency. The verification process in the blockchain technology could also cause significant energy use [56]. The energy efficiency and scalability are dependent on the consensus method and type of blockchain. There are developed consensus methods in addition to the aforementioned proof-of-work algorithm, e.g. proof-of-stake [57] and proof-of-identity [58] which are more cost and energy efficient. However, these are considered less secure than more costly consensus methods [59] [48]. A scalability trilemma is consequently introduced in the infancy of the blockchain technology, where it is argued that there is a trade-off between scalability, security and proper decentralisation [60]. However, extensive research is done on the area of scalability of blockchain, and Ethereum is currently working on a more scalable platform [61].

Privacy
Ensuring privacy is a part of protecting the consumers in the system. When more personal data are collected about the consumer, it is crucial to store it safely and not misused. Due to the transparency, the transactions and information in smart contracts on the blockchain are

stored, and hence visible to all nodes. Some level of privacy can be preserved by not linking the participating node to the owner. However, this can not be considered a fully secure method, as there is still a chance that users are recognised based on information and transactions. A common misinterpretation is that privacy, in the form of confidentiality, is preserved on a private blockchain. The information is still accessible to all the nodes included in the private blockchain. Blockchain technology can be used to manage and protect personal information in a system [62], and there are multiple blockchain protocols in development with a focus on privacy [63].

Blockchain technology is immature, but further developments are moving in high speed which gives great potential for tackling the problems on scalability and privacy. The development or choice of a blockchain protocol for various applications has to be carefully considered and furthered investigated. However, choosing a blockchain protocol is beyond the scope of this work.

3.3 Applications in smart grids

By analysing the blockchain technology characteristics, it can be recognised that the power system operation and control in liberalised markets have the similar characteristics, with multiple roles and participants, high-reliability needs and implementation of ICT with wide coverage. This section presents the role blockchain technology can play in supporting energy transition by contributing to a dynamic, efficient and competitive energy system with consumers at heart as a tool in the increasingly complex power system.

3.3.1 SGAM interaction

Emerging information and communication technologies, such as blockchain can be strong drivers for non-traditional business models, which interact in the business layer in SGAM. As investigated in Chapter 1, new decentralised and small market players, such as prosumers and service providers, are expected as future power market players. Blockchain technology is considered as a potential technology to transform power markets by enabling interactions in a more decentralised power system. The changes impact regulations contributing to the energy policy goals already covered by the Network Codes, but can also meet regulatory barriers, where new regulations might be demanded. Regulations are included in the business layer. The decentralised system architecture of blockchain allows local energy trading, empowering end-consumer by allowing the participation of demand response and services. The potential for rapid microtransactions can also contribute to real-time pricing as an important mechanism for further renewable energy integration. Therefore, the blockchain can be a tool for the functions and services described in the function layer of SGAM. The blockchain as information technology for the information exchange is described in the information layer. The blockchain protocol process data while ensuring cybersecurity, which are functionalities operational on this layer. In [64], it is shown that smart grid energy trading based on blockchain technology can increase privacy and security compared to traditional energy trading. Application of blockchain in smart grids interacts in the communication layer and component layer as well. Blockchain system requires communication between the nodes, that each has a device that can interact with enough storage capacity. Hence, blockchain technology has the potential to affect use cases in all the interoperability layers of SGAM. The blockchain technology can contribute to the ICT requirements described in the information and communication layers in a use case to potentially disrupt the functions, services and business models presented in the function and business layers.

3.3.2 Initiatives

Decision-makers in the energy sector claim that blockchain can be a solution to interrelated challenges in the energy system [65]. There are many application scenarios for blockchain in the electrical energy system, and there are already multiple blockchain projects and research initiatives in the sector [66] [67]. In a brief on the innovation landscape of blockchain for a renewable-powered future by The International Renewable Energy Agency (IRENA) [9], the blockchain initiatives in the power system are grouped into the following categories.

Peer-to-peer power trade

The most common use of blockchain in the power system is in peer-to-peer energy trading [9]. The decentralised business model enables the entry of end-users to the market, and the instant payment ensures financial settlement between participants. Local and decentralised energy systems, such as microgrids, have to integrate multiple, independent actors. With a local market structure on a blockchain, direct energy trading between consumers and prosumers can be enabled. The peer-to-peer trade contributes to the right to choose the energy supplier in the liberalised market.

A well-publicised utilisation of blockchain is the Brooklyn Microgrid project [68]. The project is a microgrid energy market in Brooklyn, New York run by LO3 Energy [69]. The world's first peer-to-peer energy transaction was made on the blockchain platform in 2016. Brooklyn microgrid is a blockchain-based microgrid and a local energy market (LEM). It consists of both a virtual microgrid for the community market and a physical microgrid, where the LEM is based on a private blockchain. A similar platform is the Power Ledger. Power Ledger is a technology startup enabling energy trading using blockchain technology. The platform supports a growing number of energy trading applications, including peer-to-peer trading. The utilities Vattenfall in Sweden, Axpo in Switzerland and National Grid UK are launching peer-to-peer energy trading platforms.

Grid management and system operation

The decentralised blockchain-based markets can contribute to the stability and security at a local level, where near real-time trading ensure local supply-demand balance. Higher time resolution on trading also enables time-varying prices, establishing the potential for demand response and ancillary services giving price signals. Moreover, smart contracts can create imbalance settlements related to supply or demand forecast errors. Decentralised, local markets decrease congestion in the power grids, as less power is transmitted between areas.

The aforementioned Brooklyn microgrid has built a physical microgrid in addition to the existing traditional distribution network in the area. The microgrid normally uses the main grid to maintain the balance of supply and demand. However, the physical grid creates the possibility of operating the microgrid in island-mode in case of disturbances on the main grid, increasing reliability. An approach that investigates demand response is proposed in [70] by C. Pop et al. A decentralised blockchain mechanism is used to provide *"transparent, secure, reliable, and timely energy flexibility"* in low and medium voltage grids. This provides a solution that includes consumer and prosumers in the flexibility market with quick imbalance corrections, coping with local problems. The demand response is managed, controlled and validated in a distributed manner utilising blockchain technology.

Financing renewable energy development

The peer-to-peer energy trading facilitates the increasing distributed generation by providing small actors and prosumers access to energy markets where they can sell excess energy. The potential for rapid microtransactions can also contribute to real-time pricing as an essential mechanism for further renewable energy integration and penetration.

A payment system for renewable energy can be created seamlessly on blockchain, creating pay-as-you-go energy for households near the generator. M-PAYG provides this as a solution for solar energy, intending to give rural areas in the developing world access to renewable energy [71]. Additionally, direct funding of renewable energy can be done using blockchain. MyBit crowdfund solar panels by distributing the ownership of the panels, using the MyBit token as cryptocurrency [72] SolarChange launched the cryptocurrency SolarCoin in 2014 to reward solar energy producers and is now one of the largest solar platforms in the world [73].

Management of renewable energy certificates

Another potential use of blockchain is for renewable or carbon certificates. The tamper-proof, transparent log of transactions, the movement and origin of what is transacted can be confirmed. This enhances the information about generation resource and opens up for a direct choice of supply and certification of origin. Blockchain can automate the issuing of certificates, with reduced costs and higher reliability. Additionally, the characteristics of the technology can include small energy producers in a green certificate procedure. There are, however, some barriers as the verification of the provided service has to rely on correct metering connected to energy production. Nasdaq created a successful blockchain trading platform of green certificate for solar energy in 2016 [74]. Both CarbonX [75] from Canada and Energy Blockchain Labs [76] from China create platforms for decentralised carbon trading. The SolarCoin platform is also an initiative for renewable energy certificates.

Electric mobility

The decentralised nature of electric mobility, with multiple parties, have promising use cases for blockchain application. Blockchain technology can create a platform integrating the actors and underpins the interactions and transactions in a secure, interoperable manner. The Share&Charge foundation developed a platform for peer-to-peer transactions between EV users and private EV charging infrastructure owners, promising a seamless, smart and secure charging experience. A TSO in the Netherlands is developing a blockchain-based system for integration of storage systems, including EVs, into the electricity grid where they can contribute with flexibility services [77].

It can be observed that there are multiple promising blockchain applications in the power system. Blockchain technology can enable end-user entrance, autonomy and new services for more transparent decentralised power markets. For utilisation in the complex electrical power system, the overall complexity of the technology increases. Clear and consistent regulations are one of the key factors to enable deployment of blockchain solutions in smart grids [9]. Proper use case development reveals benefits and uncertainties that can be used to adapt regulations. Additionally, use cases can be used to figure out strategic blockchain applications for user-friendly solutions. To perform a more focused analysis of blockchain technology as a tool for bringing the consumer to the heart of the power system, a concrete smart grid use case will be developed. Electric vehicles are rapidly penetrating the power system, and new business models withing electric mobility can provide services both to the user and for power system operation. The potential of blockchain technology applications in electric mobility will be further investigated in the following chapters.

Chapter 4

Electric vehicles in smart grids

One of the focal points in smart grids is to fully integrate the growing electric vehicle fleet into the power system [78]. Electrification of the transport sector puts forward new challenges but also introduces new services and business models. Electric vehicles are mobile, and the users desire user-friendly charging infrastructure accessible where and when needed. Electric mobility is a part of a more decentralised power system, where electric vehicle charging is a fundamental use case. Further adoption of EVs can be facilitated by creating cost-efficient e-mobility systems with better information flow and automated charging and payment. This requires interoperable information and communication networks for the e-mobility infrastructure [79], where there is potential for blockchain-based systems. To advance the current electric mobility system, use case development, as described in Chapter 2, can provide the required overview for evaluating challenges and possible extensions, where electric vehicle charging is the fundamental use case.

As explained in Chapter 2, the SGAM framework is developed to ensure interoperable systems in smart grids. In this chapter the electric mobility use case "electric vehicle charging" is modelled according to the SGAM methodology. The use case includes the actors and functions involved in achieving the primary goal of charging the electric vehicle. The use case is further mapped into the function layer of the Smart Grid Architecture Model to show smart grid interactions and interoperability in the use case. The function layer is the link between the information layer and the business layer, describing the functional use case elements. The results from this Chapter is used in the following chapter, Chapter 5, for functional analysis of the potential for blockchain application in the specific smart grid use case.

4.1 Introduction to electric mobility

The electrification of the transport sector, as introduced in Chapter 1, is interrelated with decarbonisation, decentralisation and consumer empowerment in the future power system. The electric vehicles present a new type of load in the power grid, with potential for consumer engagement and new markets.

4.1.1 Electric vehicles in power system operation

A growing EV fleet challenges the distribution system operation, as a power demanding load. The charging of the EVs from the electricity grid can have a sizeable impact on capacity requirements at certain hours and locations. Charging often coincides with the existing load demand, which stresses the local grid and can have consequences for the adequacy and quality of supply [80]. As a result, it can require additional investment in grid and generation capacity. However, from the perspective of the power system, EVs can be regarded as distributed, flexible loads and storage systems. The charging of an EV is separated from the use, and can hence contribute to demand-side flexibility for enhanced grid stability and reliability.

Electric vehicle charging is separated into uncontrolled and controlled charging, often referred to as respectively dumb and smart charging. The dumb charging is when the EV is plugged in and charged at maximum power until fully charged. On the contrary, smart charging is *"when the charging cycle can be altered by external events, allowing for adaptive charging habits, providing the EV with the ability to integrate into the whole power system in a grid and user-friendly way"* [78]. The smart charging benefits the customer by reducing electricity costs while supporting system operation. The management of the charging process can be divided into three different scenarios, according to control objective: peak shaving scenario, renewable scenario, and balancing scenario [81]. The controlled charging can hence contribute to varied ancillary services for the power system operation. An electric vehicle can also provide bidirectional charging by vehicle-to-grid (V2G), where the EV also can inject power back to the grid and increase the operating range for demand response services as distributed batteries.

The control is further separated into direct and indirect control of the charging [82]. Direct control is centralised decision making and management of the demand side by remote control. Indirect control relies on decentralised decisions, e.g. by signals from the DSO on the desired behaviour where the EV user itself can choose to respond. Demand response from EVs relates to the need for remodelling electricity markets, as discussed in Chapter 1. The utilisation of local flexibility emerges as a potentially cost-efficient alternative in future power system operation [83]. New market mechanisms are demanded for energy flexibility to encourage better utilisation of DER and consumer engagement in smart grids. An additional requirement for adopting demand response solutions is a proper use of ICT to connect the participants, where real-time information and price signals can be delivered in a standard format to small consumers [83].

4.1.2 Functional requirements of the users

Consequently, in addition to a safe supply of electrical energy, ICT improvements are needed to further empower the end user in the system. ICT can also enhance the charging experience for the EV user. A survey reveals that users are concerned for the driving range of electric vehicles, and appreciate reliable, automated charging systems that guarantee a sufficient state of charge (SOC) for use [84]. There must be convenient access to charging stations, with adequate availability and standardised, automated processes and seamless use. Ideally, the consumers have the option to share their charging stations for potential revenue and increased utilisation of resources. The costs of operating and using charging stations should be minimised, with the potential for smart charging. The electric mobility market is expected to be decentralised, with multiple systems and individual participants with complex interactions. Additionally, the decentralised e-mobility market makes it increasingly challenging to ensure mutual trust. Processing of payments has to be secure for all actors involved. The complexity also challenges the privacy with potential for surveillance and attacks [85], making it increasingly important to assure the privacy of the user.

4.2 Use case: Electric vehicle charging

The use case ”electric vehicle charging” is developed and described in this Section. The short version of the use case modelling described as part of the SGAM methodology in Chapter 2 is used, as the functions and interactions between actors are of relevance for this work. However, the use case can be extended to include more detailed descriptions if necessary for further or other applications.

The scope of electric vehicle charging is a charging process of an electric vehicle with energy from the electrical power system. The EV user needs sufficient energy stored in the EV battery for desired driving. Therefore, the EV charging system aims to provide adequate power and energy delivery to the EV according to the preferences of the user. As the preferences of the user are likely to include objectives concerning price minimisation, the charging in this use case can be categorised as smart charging. The charging can occur at both publicly or privately accessible charging stations. However, the use case is specially designed for charging outside the users home premise, as this has additional requirements and complexity compared to charging at home. A charging session is initialised as the EV user plus in the EV at the charging station. Here it can choose to included preferences, e.g. charging time, demand response participation. The charging system controls the charging in regards to the user's preferences. The EV charging is finished when the demanded SOC is reached, or if the user unplugs the

EV from the station. The use case also includes the economic aspects of each charging session to ensure settlement between involved parties.

4.2.1 Actors

Multiple actors are involved and interact to achieve the goal of charging the electric vehicle. To develop a use case that is standardised and compatible, the actors described are aligned with the electric mobility actors from a report about smart charging in relation to smart grid by the CEN-CENELEC E-Mobility Coordination Group (M/468) and CEN-CENELEC Smart Grid Coordination Group (M/490) [78], and COTEVOS, an EU project on electric vehicle interoperability COTEVOS [86]. The identified e-mobility actors with their respective roles in the use case are presented in Table 4.2. The actors include the EV user as the primary actor, devices and supporting stakeholders, assisting the primary actor in achieving its goal.

Actor	Actor type	Description of role
Electric Vehicle (EV)	Device	The electric vehicle is the machine that is charged with electrical energy by charging equipment in the use case, and is used by the EV user.
Electric Vehicle User (EVU)	Primary actor, person	The electric vehicle user is the person utilising the charging system to charge the EV it is using and pay for the service. The goal of the EVU is to have the EV sufficiently charged when needed according to its preferences.
Electric Vehicle Supply Equipment (EVSE)	Device	The electric vehicle supply equipment is the charging infrastructure for supplying energy to recharge the EV. It physically connects the EV to the grid and ensures power flow as requested within given standards and constraints.
Charging Station Operator (CSO)	Organisation, system or person	The charging station operator maintains and controls the operational functionality of the EVSE. The CSO and EVSE combined is the charging station. By a charging management system (CMS), the CSO manages the EVSE and can add smart charging functions.

E-Mobility Service Provider (EMSP)	Organisation or system	The E-Mobility Service Provider manages the services needed for the EV charging. The EMSP has contracts with the EVU and the CSO and ensures communication between the parties to allow the EVU to charge its EV at the EVSE. It can be extended to provide additional value-adding services, for example, reservation of charging stations.
Clearing House (CH)	Organisation or system	The clearing house provides information and economical clearing services between the CSO and the EMSP. It manages the data exchange and payments between the operators in a neutral manner, to facilitate the exchange between the parties. The CH hence ensures an interoperable EV charging with open access to charging stations.
Distribution System Operator (DSO)	Organisation	The distribution system operator is responsible for ensuring a safe supply of electrical energy to EVSE and EV. The DSO can also have a goal of acquiring demand response services from the EV charging, and consequently, give signals and incentives for adjusting charging to this if desired by the EV user.
Electricity Supplier (ES)	Organisation	The electricity supplier provide the electricity to the EVU from a contractual point of view.

Table 4.2: Description of the actors in electric vehicle charging.

The identified actors can be mapped into their respective domains and zones in an SGAM layer, as shown in Figure 4.1. The layer can be regarded as a simplified component layer representation, which could be developed further by transforming the actors into the related components in the charging system. However, this is not relevant to the scope of this thesis.

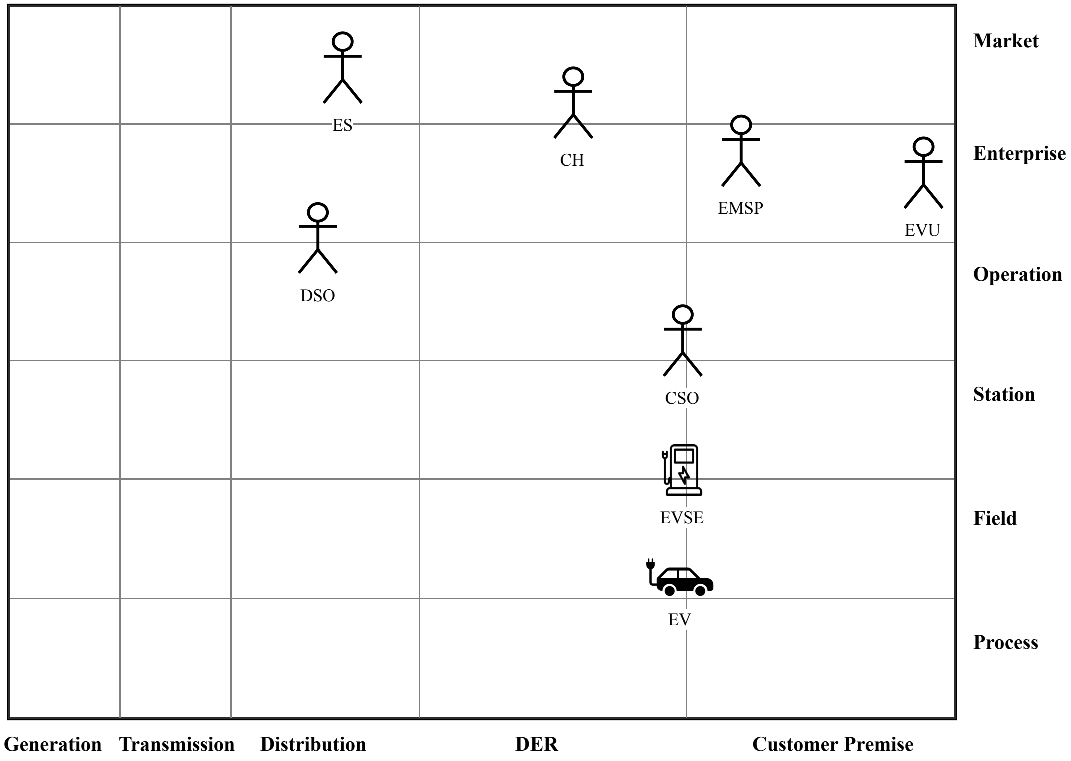


Figure 4.1: The actors mapped in SGAM.

4.2.2 Functional description

The high-level use case ”electric vehicle charging” can be decomposed into the functions involved. The functions are extracted from the EU consortium FINSENY about smart energy[87] and the ISO 15118-1 standard [84]. The ISO 15118 standard series covers the communication between the electric vehicle and a charging station required for the charging process. The first part of the standard, ISO 15118-1 cover the high-level information and understanding of the functions and defines the primary use cases or functionalities of the charging process, and group them into functions. The ISO 15118 functions are restructured and combined with the functions from FINSENY, to create a high-level use case that involves all required functions involving the actors.

Plug in:
The EVU physically connects the EV with the EVSE. Necessary for power flow to the EV. Actors involved: EVU, EV, EVSE.

Authorisation:
Authorisation includes identification and authentication. When the EV is plugged in, the EVU requests an authorisation to use the charging station. The EMSP establishes a connection between the EVU and the CSO through the CH. The EVU is identified, and it is determined if

the EVU can be granted charging access. Depending on the charging system, this identification and authorisation methods differ. The authorisation involves checking if it is secure to provide the charging service, for example, by checking if the EVU has sufficient funding for payment.
Actors involved: EVU, CSO, EMSP, CH.

Scheduling:
The scheduling includes data acquisition, target setting, tariff management, and charging optimisation. The schedule includes relevant information to optimise the charging, and the function invokes acquisition of SOC, demand and preferences from the EVU and tariffs from the ES. The CSO creates a charging schedule by with success conditions to reach.
Actors involved: CSO, EVU, ES.

Energy supply:
Electrical energy is supplied from the distribution grid to EV through the EVSE.
Actors involved: DSO, EVSE, EV.

Control:
The energy supply is controlled, monitored and metered in the control function. The CSO controls the EVSE according to the charging schedule, allowing power flow at instructed standards until success conditions are reached. The control includes monitoring of the charging process, and energy metering, which is crucial for correct billing of the EVU. The control may involve re-scheduling, for example, if real-time demand response is included.
Actors involved: CSO, EVSE, potentially DSO.

Plug out:
The EVU physically disconnects the EV from the EVSE. This unconditionally cancels the charging process, regardless of the state of charging schedule.
Actors involved: EVU, EV, EVSE.

Payment:
The payment functions involve rating, clearing, billing and settlement. The EVU pays for the services connected to the charging. The payment process varies depending on the system. It can be prepaid as a deposit may be withheld from the authorisation and scheduling process, it can be near real-time payment during the actual charging or traditional post-payment after rating. Rating is calculating prices based on metering data and tariffs. The CH clears the payment between the CSO and EMSP, and the amount that should be paid by the EVU is billed. The payment is finalised by settlement between the actors of the billed amount.
Actors involved: EVU, CSO, EMSP, CH, ES, potentially DSO.

4.2.3 SGAM Function layer

Figure 4.2 shows a proposed mapping of the use case on the SGAM function layer. It illustrates the interactions between the actors in the functions for the process of electric vehicle charging, where the coordinates related to the smart grid zones and domains are considered.

Concerning the power system conversion chain, the functions in the charging process mainly occur in the DER and Customer Premise domains. The energy supply, however, also involves the distribution domain. The mapping of the functions in SGAM is also regarding the zones in the smart grid. The local, physical functions, as plug in and out occur in the field zone. The station zone includes the local control in smart grids, such as the control function. However, the scheduling includes interactions in higher hierarchical zones and can be placed in the operation zone. The operation zone provides operations related to the authorisation. The enterprise zone covers customer relations management, such as parts of the authorisation and payment. Further, the payment function involves market operations and is hence also in the market zone.

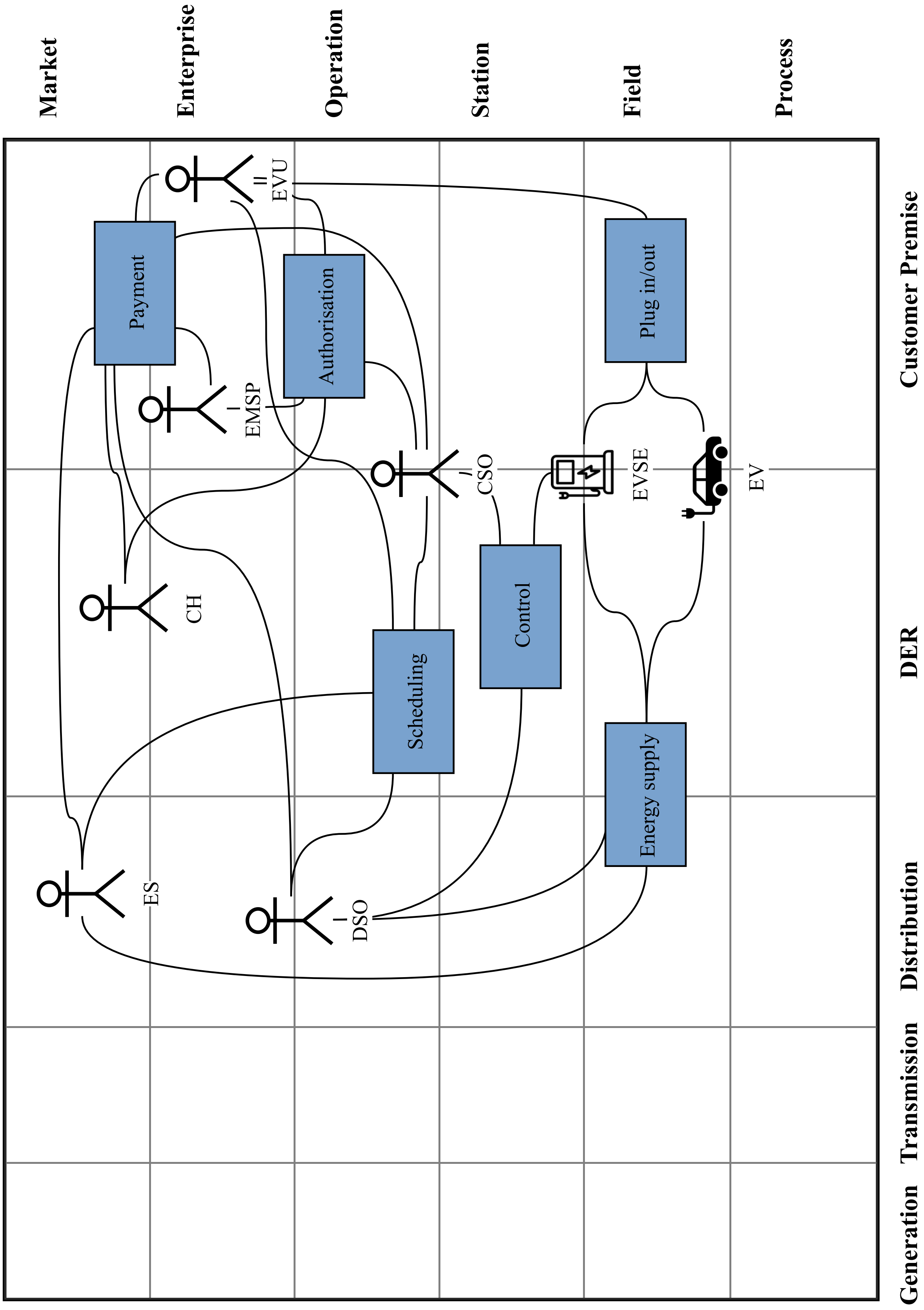


Figure 4.2: The use case in SGAM function layer.

In this chapter, the use case "electric vehicle charging" was developed, and the functional layer described. The EV users need access to charging infrastructure to charge its electric vehicle, which creates a complex system with multiple actors and functions. The user requirements described emphasise the need of ensuring the right data to the right needs for a secure, trusted and preferably automatic system, which is dependent on the integration of ICT. Furthermore, advantageous ICT utilisation in the system can fundamentally contribute to power system operation needs, as a decentralised network that connects users can facilitate for consumer participation in new business models and services as described in Chapter 1. As investigated in Chapter 3, blockchain has potential to support interactions in smart grid use cases for necessary information flow, in a secure, decentralised manner. The use case developed will be used in the following chapter to analyse how blockchain can be implemented in the electric vehicle charging, for putting consumers in the centre and strengthen the end user's interest.

Chapter 5

Blockchain in electric vehicle charging

Blockchain technology has potential as information technology for interoperability in smart grids, as elaborated in Chapter 3. Blockchains processes transactions directly between parties in a secure manner, without the need for intermediaries, and provide smart contracts for self-enforcing transactions following contractual agreements. The decentralised nature of e-mobility with multiple actors and complex interactions creates a good basis for blockchain applications. It is important to utilise the technology in a beneficial way adapted to the use case, while highly considering the end user's interests as a primary stakeholder in the system and a priority in energy policy targets. Application of blockchain technology as a tool in the EV charging system can be properly investigated using the use case from Chapter 4.

This Chapter presents an analysis of how blockchain technology can be applied in the developed "electric vehicle charging" use case. The requirements of the use case and the latent benefits of blockchain are considered for a strategic fit, and the SGAM is used to examine and highlight the functional application of blockchain in the use case.

5.1 Application potential

The blockchain technology can create a decentralised charging information system for transactions in the use case. The information technology can be a tool in bringing the consumer to the heart of the system, as an enabling technology for the required functions and interactions in the use case.

Reduce interaction and information frictions

Interaction friction is a limitation in the electric mobility system, magnified by the many actors and interactions required. Blockchain's peer-to-peer architecture removes barriers for participation and connection between participants. It allows the EV users and the EVs to dynamically engage in the distributed energy trading and sharing of resources independently of central third parties. The participants can directly exchange assets, and hence reduce the complexity of multiple transactions, while reducing processing time and costs. The design of blockchain removes the need for intermediaries in transactions, and can consequently reduce redundant supporting actors in the system. As a small participant in a complex system with multiple stakeholders, the EV user might experience imperfect and inaccessible information. The shared ledger in blockchain decentralises the information flow and decisions and provides transparency. This ease the information friction in the system.

Secure information and transactions

Security is an additional aspect that has increased importance with the complexity connected to multiple actors and interactions in a charging system. The user benefits from increased trust and safety in the system, and the EV charging especially requires that the processing of payment transactions can be trusted. It is important to remove the vulnerability of cyber-attacks and fraud due to the involvement of numerous and potentially unknown, untrusted parties. One of the main features of blockchain technology is that the trust lies in the technology itself, with consensus-mechanisms and cryptography. The contractual relationships between the parties in EV charging have to be managed in a safe manner. Due to the smart contracts in blockchain, the transactions can be rule-based and triggered automatically.

Interoperable and innovative systems

Hence, there is a potential for blockchain to increase innovation and enable the development of new business models. As explored in Chapter 1 and Chapter 4, there is an expected emergence of non-traditional business models in smart grids and electric mobility. The cost of complexity can be eradicated and the boundaries of a system redefined. Establishing a blockchain system for the economics and information flow as a standard solution could contribute to increased adoption of electric vehicles. A blockchain-based charging system for processing identification and payment transaction creates a more seamless experience for the EV user by providing interoperability. The interoperability simplifies the charging process for the EV user as the authorisation and payment when utilising a new charging station could occur autonomously. It can also minimise the barrier for sharing charging infrastructure, by assuring simple, cheap and secure transactions. Additional services to and by the EV user are easier to include with a decentralised information technology that reduces market friction.

5.2 SGAM interaction

Applied to a smart grid use case, the features of the blockchain technology enable data exchange and information flow described in the information layer of the SGAM. The information flow underpins the interactions between the actors for the functions described in the function layer, necessary for the business goals in the business layer. The functional architecture and the actors in the ”electric vehicle charging” use case can be recalled from Chapter 4. Based on the characteristics of Blockchain as information technology, the *plug in*, *plug out* and *energy supply* functions, which are related to physical actions and power flow, are thus not relevant for blockchain application. There are, however, potential application scenarios for the remaining functions where the exchange of data and managing contracts can be supported by blockchain. The EV user is the primary stakeholder with the goal of charging its EV, while the charging station, comprising the CSO and EVSE, the DSO and the energy suppliers necessary actors to provide electrical energy to the EV. However, the actors CH and EMSP have roles related to information flow, enabling necessary interactions for the functions. The roles of CH and EMSP as intermediaries between CSO and EVU can hence be performed by a blockchain-based charging system. Figure 5.1 illustrates the functions, interactions and roles blockchain can have in the ”electric vehicle charging” use case marked in red.

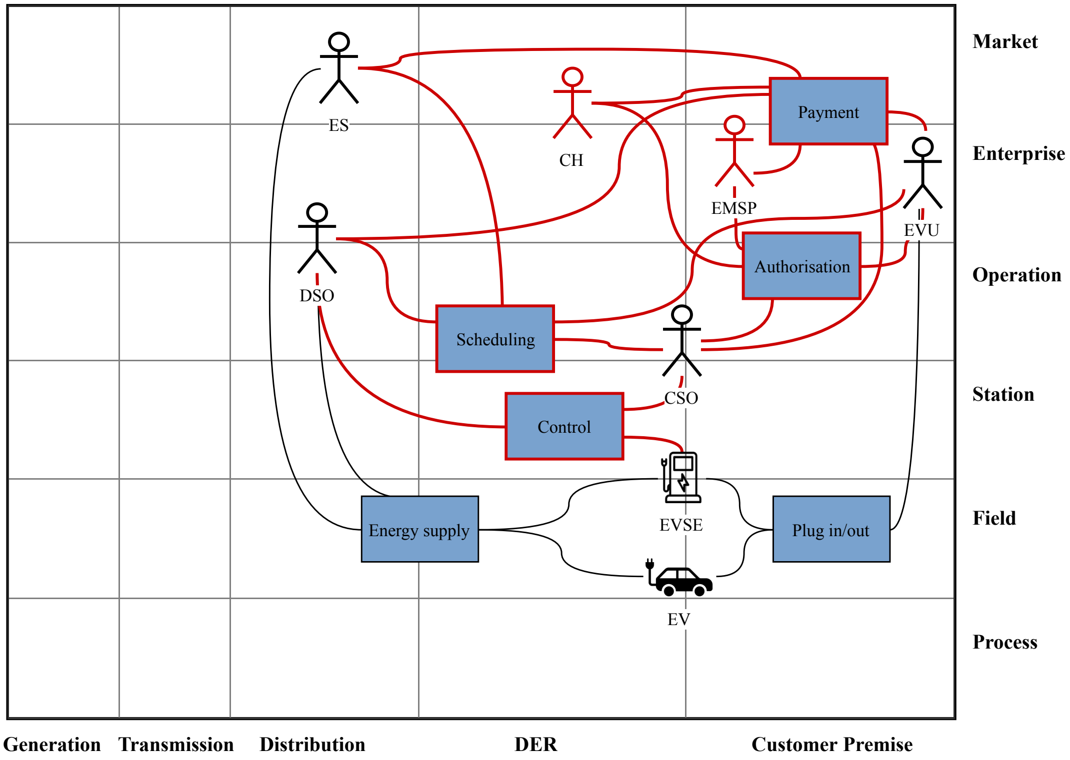


Figure 5.1: Blockchain interaction in SGAM for electric vehicle charging.

User management in a blockchain-based charging system can be handled by the blockchain platform. All electric vehicle users and individual charging station operators can participate as a node in a blockchain-based charging system. The personal blockchain address for each participating node can be used to create user accounts with relevant information stored on the blockchain. This can underpin the authorisation function in the use case. Exchange of relevant information for scheduling and control functions can flow on the blockchain platform, such as preferences and real-time price signals. The optimisation of the charging schedule can be performed on the blockchain by a smart contract including the relevant information from the different actors as input. The blockchain, as a distributed database, can store charging related data, such as metering data from the control function, where the information is transparent. Processing the charging payment function is highly relevant on a blockchain system. The billing and settlement of charging procedure can occur seamlessly on the blockchain, where smart contracts allow for automatic and secure payments. The smart contracts can also perform the calculation relevant for rating and clearing of payments. The payment can be performed without the need to share sensitive information with other actors, while the actors still are guaranteed payment for the provided service. The removal of interaction friction facilitates for implementation of more rapid settlement and near real-time payment. As the payment transaction occurs on the blockchain, the details are stored on the distributed ledger which ensures authenticity and transparency of the payments.

Chapter 6

Application scenario and proof of concept

There are different scenarios for application of blockchain in electric vehicle charging. However, this Chapter proposes a specific application of blockchain technology for the functions involved in EV charging. Furthermore, a proof of concept is performed by implementing the application scenario on the Ethereum platform to investigate the technical feasibility of a blockchain-based information system in the use case.

6.1 Functional description

The blockchain application is a tool in the charging of the EV for the EVU as the primary goal of the use case. Additionally, it facilitates for the CSO to share its charging infrastructure, the ES to sell energy and the DSO to request demand response. Smart contracts ensure contractual and monetary functions, interactions between actors and integration of relevant data with correct origin in a secure manner. The blockchain implementation eliminates the EMSP and CH as intermediaries by taking their roles, and creates a trusted, transparent and interoperable charging system. The charging process on the blockchain is initialised and then updated on regular time steps. This arranges for near real-time payment, where the charging is settled on each time step. As discussed in the previous sections, the decentralised information system reduces the barrier for further extensions and value-adding services. The functionality of demand response can easily be added if the DSO is involved in the network, as demand response signals can be transmitted directly to the user and automatically processed. The connection between the actors in the blockchain-based charging system is illustrated in Figure 6.1

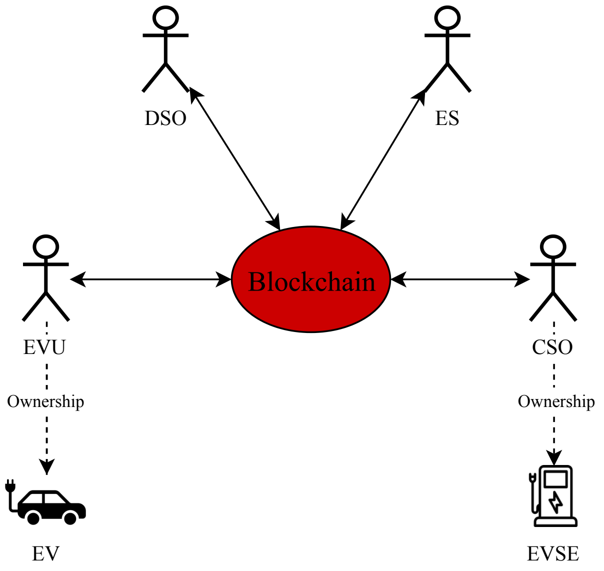


Figure 6.1: Actors and interactions in the blockchain-based electric vehicle charging.

The scenario requires prerequisite functions that are not related to an individual charging process. The actors in the charging system include electric vehicle users, charging station operators, energy suppliers and the DSO, and they have to be registered and specifically assigned to the correct role in the charging system on the blockchain. The actors have to be nodes on the blockchain to add information, call functions and read data in the system. For example, the CSO role includes information about the charging station, regarding the available charging level and price for using the station. Additionally, the actors have to manage their token balance. The token is a virtual currency connected to the charging system, and only an authority is allowed to modify the currency balance on the blockchain. Hence, the blockchain system requires an authority that sets the system and manages the withdrawing and deposit of real money.

The functions involved in each charging process is as described in the use case ”electric vehicle charging”. The functional order of a charging session in the application scenario is presented in Figure 6.2, where the functions involving blockchain interactions are marked in red.

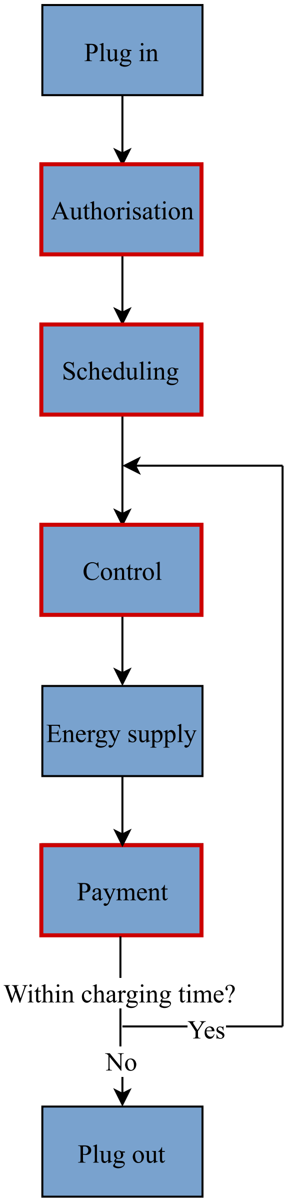


Figure 6.2: Blockchain-based electric vehicle charging process.

A charging process starts with the EV user plugging in the EV in the EVSE, followed by a request for authorisation to charge at the charging station. The following electric vehicle charging functions on the blockchain is as follows.

Authorisation:
The authorisation function is performed on the blockchain when called. It verifies that the EVU and the CSO for the charging session are registered in the smart contract of the charging system and that the EVU has a sufficient token balance. If the requirements are met, a new charging session in initialised where the process is marked as connected, and the ID of the EVU and the CSO are stored. Successively, the EVU is notified that it is authorised to charge.

Schedule:
When the EVU is notified that it is authorised to charge, it adds information on charging time and energy demand on the blockchain. This further notifies the energy supplier to include energy prices for the time interval. When necessary data are gathered, the CSO asks for the creation of a charging schedule. The schedule is only created if the necessary information is added and the process is connected. The schedule follows the rules in the contract by considering energy demand, power level, charging time and prices, ensuring sufficient energy at minimal cost for the EVU. In addition to a schedule, the function creates a list to audit settlements. Following, the CSO fetch the schedule from the blockchain.

Control:
The control is partly done on the blockchain in this application scenario. The CSO invokes the control function in the smart contract for pre-defined time steps in the charging time. It updates the information on SOC of the EV. The control function also responds to real-time demand response signals from the DSO, and updates the charging schedule if it meets the EVU's criteria and can be accepted. If the EVU has ended the charging, the charging process is updated to disconnected. However, the actual control of the EVSE according to the schedule is done off the chain.

Payment:
Corresponding to the frequent control, the payment function is performed each time step. If the EV has been charging and the time step is not formerly settled, tokens are transferred from the EVU to the CSO and the ES respectively, and from the DSO to the EVU if it responded to demand response signals. When a time step is settled, the settlement list is updated, preventing double payment. The payment uses the internal functions to transfer tokens, and tokens can therefore not be transferred unless the criteria in the payment function are met. If the end of the charging time is reached, the charging is marked as disconnected.

The EVU plugs out the EV when the charging process is finished.

6.2 Software implementation

To further examine the feasibility, a proof of concept is made on the application scenario. The proof of concept is performed to confirm that the application can be implemented on blockchain and provide the expected features and simulation results.

The use case is implemented in the Ethereum blockchain environment. This is due to the suitability for the creation of decentralised applications (dApps). Ethereum is open-source, with extensive available documentation and allows anyone to write and deploy smart contracts with free development tools and test networks. Deployment is to send the smart contract to a specific address on a blockchain, so it can be accessed decentralised and nodes can run the functions in the contract.

6.2.1 Smart contracts for functions

The smart contracts in Ethereum can be written in programming languages that are designed to target the Ethereum Virtual Machine (EVM). The EVM is the part of the Ethereum blockchain protocol which executes code and handles the internal state of the blockchain. Solidity is an object-oriented, high-level language for implementing smart contracts [88]. Solidity is chosen in this work for the implementation of smart contracts due to access to resources. However, there does exist other contract oriented languages for Ethereum such as Vyper.

A smart contract is created for the charging process. The full smart contract code is included in Appendix A. The smart contract design ensures correct data handling, setting rules for adding data and running functions. The smart contract ”evcharging” is deployed on the blockchain If a function adds or modifies values included in the smart contract, it is stored as a transaction on the blockchain. Hence, a smart contract makes sure that all data added and created in the charging process are stored on the blockchain and are transparent to the nodes. The smart contract ensures that conditions for transactions are met. One important type of smart contract rule is regarding who has permission to run a function.

To process a charging session on the blockchain, the prerequisite functions have to be handled. The ”evcharging” contract includes functions for setting the system, such as *newEVU* and *setDSO*, which only an authority in the system can invoke. It is assumed that there is only one charging power level and that the EV is either charging at this power or not. The structure of the smart contract functions corresponding to the use case functions are as follows:

Authorisation:

```
//The EVU requests authorisation to charge at the CSO with the address of the CSO.
function authorisation(address _csoAddr) public {
```

```
    //Checks that the EVU is registered in the system, and is the one requesting the charging process:
    require(evuList[msg.sender].addr == msg.sender);
    //Checks that the CSO is registered in the system:
    require(csoList[_csoAddr].addr == _csoAddr);
    //Checks that the EVU has enough tokens to charge:
    require(evuList[msg.sender].tokens > limit)
    //Create an ID for the charging process:
    uint cpID = numCPs++;
    //Initialise new charging process:
    Process storage p = processes[cpID];
    //Add information to charging process:
    ...
    //Sends event that the charging process is authorised:
    emit Authorised(cpID);
}
```

Listing 6.1: Authorisation function in Solidity smart contract.

The ”msg.sender” is the node running the function, which has to be a registered EVU. The function is finalised by sending out a signal in the form of an ”event” with the ID of the authorised charging process. Nodes on the blockchain can subscribe to these events, and hence the involved actors can get a notification a charging process is authorised.

Scheduling:

```
//EVU adds charging demand to the system.
function addDemand(uint _cpID, uint _chargingTime, uint _energyDemand) public{
    //Ensure only EVU uses function:
    require(msg.sender == p.evuAddr);
    p.energyDemand= _energyDemand;
    p.chargingTime= _chargingTime;
    //Sends event to ES requesting prices:
    emit requestPrices(_cpID, _chargingTime);
}

//ES adds prices for the charging process time-steps. Similar structure as the addDemand function.
function addPrices(uint[] memory _prices, uint _cpID) public {...}

//Creates an optimised schedule minimising price while ensuring energy demand. Requires necessary data to run.
function scheduling(uint _cpID) public{
    //p.schedule[t] for all t set to either true or false.
    ...
    //Sends event that schedule is ready:
    emit scheduleReady(_cpID, p.schedule);
```

```
}
```

Listing 6.2: Scheduling function in Solidity smart contract.

The EVU has to add data on its charging demand and preferences, and the ES has to add prices for the schedule to be created.

Control:

```
//CSO controls the charging for every time-step t of the charging process.
function control(uint _cpID, uint t) public {
        ...
        //Only CSO can control charging:
        require(msg.sender == p.csoAddr);
        //Checks for demand response signals from the DSO and updates schedule
            if possible to accept:
        checkDRAndUpdate(_cpID, t);
        ...
        //Updates SOC if charging.
        //Cancels the charging if EVU has disconnected.
}
```

Listing 6.3: Control function in Solidity smart contract.

The smart contract includes the function *addDRsignal* where the DSO can add demand response signals for a time step. It is assumed that it includes both up and down regulation and that the profit of contributing to demand response is larger than the expense of shifting the demand to a more expensive charging time step. Demand response signals for up-regulation are accepted if the EV is not scheduled to charge and demanded energy level not reached. Down-regulation signals are accepted if it is scheduled to charge, and there is enough time to shift the charging to a later time-step.

Payment:

```
//Near-real time payment for every time-step of the charging process.
function payment(uint _cpID, uint time) public{
    ...
    //EVU pays ES if conditions are met.
    //EVU pays CSO for every time-step it is connected.
    //DSO pays EVU if demand response signal was responded to.
}
```

Listing 6.4: Payment function in Solidity smart contract.

The *payment* function is the only function that can be run by the nodes which transfer tokens, and it requires that all conditions regarding a payment are met.

Secure as they have to follow the rules to be executed. Everything is stored on the blockchain. Restriction to changing of values and running of functions.

6.2.2 Simulation

To validate the feasibility of performing the functions in the smart contract, simulations are performed. The development framework Truffle is utilised to develop and deploy the smart contract. For the testing, a simulation is performed on a private blockchain test network using Ethereum, namely Ganache. Ganache is a part of the Truffle ecosystem, and it provides local, personal blockchains for development purposes. It creates a virtual Ethereum blockchain with virtual accounts possessing the same attributes as a real Ethereum blockchain, but without actual costs of performing transactions. Solidity is used to write smart contracts, while python is used for initiating the contracts, acting as the actors in the charging system. To connect to the blockchain, the Web3 library is used to interact with Ethereum blockchain from Ganache through python. The python script used for the simulations are included in Appendix B.

The simulations are performed with the following input data:

- Energy demand = 30 kWh
- Charging time (i.e. time connected) = 10 h
- Time step = 1 h
- Power supply = 5 kW
- Hourly prices = [1, 1, 2, 3, 3, 2, 2, 1, 1, 1] NOK/kWh
- Charging station price = 5 NOK/h
- Demand response profit = 30 NOK/h (set high as it is assumed it is always beneficial to accept)

A simulation is first performed without demand response signals, which gives the following results.

Results without demand response:

Time-step	**Schedule** (charge = true)	**SOC** (kWh)	**Change in EVU's token balance** (NOK)
1	True	5	-10
2	True	10	-20
3	False	10	-5
4	False	10	-5
5	False	10	-5
6	False	10	-5
7	True	15	-15
8	True	20	-10
9	True	25	-10
10	True	30	-10

Table 6.1: Simulation results without demand response.

Total cost for EVU = 95 NOK.
Total profit CSO = 50 NOK.

The results show that a charging schedule is created that minimise the charging costs, and the charging is operated ensuring correct energy demand and the charging is settled each hour.

Results with demand response:

Time-step	**Schedule** (charge = true)	**DR signal** (1 = up, -1 = down)	**Control** (charging = true)	**SOC** (kWh)	**Change in EVUs token balance** (NOK)
1	True		True	5	-10
2	True	-1	False	5	25
3	False		True	10	-15
4	False		False	10	-5
5	False	1	True	15	10
6	False		False	15	-5
7	True		False	15	-5
8	True		True	20	-10
9	True		True	25	-10
10	True		True	30	-10

Table 6.2: Simulation results with demand response.

Total cost for EVU = 35 NOK.
Total profit CSO = 50 NOK.

The blockchain-based charging system can hence also include demand response. The requested energy level is obtained, while the total costs of the EV charging are reduced do as the charging is shifted due to signals from the DSO. The deviations from the original schedule is market in red in Table 6.2. However, this does not affect the CSO in the system. The time-step can easily be chosen closer to real-time with the proposed smart contract code, e.g. from 1h to 15 min, to provide better flexibility.

The smart contract functions and simulation results validate the feasibility of implementing the charging system on Ethereum blockchain. It manages the information flow and payments on the blockchain, following rules on who can do what and how actions can be performed, ensuring security in the system. Blockchain system offers access to information for all the involved stakeholders. The CSO can be an organisation, a private person or the EV user itself. Consequently, the implemented blockchain system is interoperable and can be used for both public and private charging. The algorithm is simple and transparent and is easy to replicate for real demo projects for EV charging with demand response.

Chapter 7

Conclusions

Blockchain technology implementation for electric vehicle charging within the Smart Grid Architecture Model is studied in this thesis. The changes in the power system are first introduced, which explain the development towards smart grids as necessary facilitation of the interrelated trends of a low carbon economy, decentralisation and empowerment of consumers. Smart grids include new services and extensive utilisation of ICT to adapt to the new challenges. To realise the smart grid concepts, the power system has to respond to dynamic interactions between multiple actors and technologies, which creates a complex system. Here, the Smart Grid Architecture Model is presented. The approach of using SGAM in the context of smart grids is proposed to gain a better understanding of the complex systems, show interactions and discover requirements.

Blockchain technology is introduced as a novel, promising technology for applications in smart grids. By investigating the characteristics of the technology, the key features are discovered, which are decentralisation, security and transparency. It is recognised that application of blockchain can be a tool in supporting the energy transition by enabling end-user entrance, autonomy and new services for more transparent decentralised electricity markets. Implementation of blockchain in smart grid use cases can hence disrupt on multiple layers of SGAM.

A more focused analysis is performed on electric mobility in smart grids. Electric mobility can challenge power system operation, but also provide services by smart charging and demand response. The fundamental electric mobility use case ”electric vehicle charging” in smart grid is developed and further visualised in the Smart Grid Architecture Model to describe system structure, requirements and interactions. Electric vehicle charging involves multiple actors and functions which highlight the need for ensuring the right data to the right needs for a secure and trusted system, which is dependent on ICT. The use case is used to perform a functional analysis of the implementation of blockchain technology to bring the consumer to the heart of the system. Blockchain technology can create an information system reducing interaction and information friction in a charging system. The information flow and transactions involved in a charging process can be secure and transparent.

A specific application scenario for blockchain in electric vehicle charging is presented. The blockchain implementation eliminates intermediaries in the charging process and connects the actors in the system. This creates a trusted, transparent and interoperable charging system that handles authorisation, scheduling, control and payment of charging processes. The application scenario is proven feasible by implementing the blockchain-based charging system in the Ethereum blockchain environment. A smart contract ensures correct data handling and rules for adding information and running functions. Simulations are performed, which shows that blockchain implementation can ensure information flow and transactions for the necessary functions. Application of blockchain technology in electric vehicle charging can provide a more seamless and secure charging experience for the user. It can create an interoperable charging information system, facilitating for sharing of charging infrastructure and decrease the costs of operating and using charging stations.

Additionally, the functionality of sending demand response signals to electric vehicles on the blockchain-based information system is included. The signals can be transmitted directly to the user from the DSO and automatically processed on the blockchain. This can provide flexibility to system operators which can contribute solve local congestion and instability in the distribution grid while reducing the bill for the consumer in the system.

7.1 Further work

The work performed in this thesis shows that blockchain technology implementation in electric vehicle charging has promising potential. However, further considerations and tests to prove real, long-term value.

The scope of this work has led to a focus on the benefits of blockchain technology in smart grids, rather than the challenges. The thesis has a limitation in the lack of focus on the differences in the protocols of blockchain technology, and on choosing the most beneficial design of the blockchain protocol for the system. Considerations have to be made regarding scalability, privacy and permissions to the blockchain platform. This should be investigated in further work to ensure strategic implementation of blockchain. The computational complexity of functions has to be contemplated for certain blockchain protocols, due to scalability problems. Additionally, blockchain raises problems regarding information privacy and legal issues. These are important issues in smart grids and can be barriers to implementation.

Furthermore, the focus is on where the blockchain can be a tool and be implemented in smart grids, rather than if. Blockchain applications as novel solutions also have to be compared to other solutions, e.g. traditional databases, to make sure it is a beneficial implementation.

The implementation of a blockchain-based system requires a full understanding of the technology and proper creation and management of the system, as the correct design of a blockchain application is crucial to ensure the latent security from the blockchain protocol. The technology can secure the data added on the blockchain, however, the blockchain cannot validate the authenticity of the metering data included. This would need to be considered, e.g. by a standardised, trusted connection of smart meters to the blockchain. Additionally, a proper user interface and adequate user devices and communication infrastructure have to be considered for real-life implementations.

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Appendix A

Solidity Smart contract

```
pragma solidity >=0.4.21 <0.6.0;

contract evcharging{
  //PREREQUISITE FUNCTIONS - Set the system
  address authority;
 mapping (address => EVU) public evuList;
 mapping (address => CSO) public csoList;
 address public es;
  address public dso;
  uint public drPrice;

  constructor() public { //Decides who is the authority, and can only be run once at the beginning.
    authority = msg.sender; //used for functions that only the authority can access and modify
  }

  struct EVU {
    address addr;
    uint tokens;
    uint SOC;
  }

  struct CSO {
    address addr;
    uint tokens;
    uint power; //available power at charging station
    uint price; //price for using the charging station
  }

  function setDSO(address _dso, uint _drPrice) public{
    require(msg.sender == authority);
```

```
        dso = _dso;
        drPrice = _drPrice;

    }

    function setES(address _es) public{
        require(msg.sender == authority);
        es = _es;
    }

    function newEVU(address _evuAddr) payable public{
        EVU storage evu = evuList[_evuAddr];
        require(msg.sender == authority);
        evu.addr = _evuAddr;
        evu.SOC = 0;
        evu.tokens = 0;
       // ev.energyDemand =0;
       // ev.chargingTime =0;???
    }

    function changeTokensEvu(address _evuAddr, uint _tokens) public{
        require(msg.sender == authority);
        evuList[_evuAddr].tokens += _tokens;
    }


    function newCSO(address _csoAddr, uint _power, uint _price) public{
        require(msg.sender == authority);
        CSO storage cso =csoList[_csoAddr];
        cso.addr = _csoAddr;
        cso.power = _power;
        cso.price = _price;
        cso.tokens = 0;
    }

    function changeTokensCso(address _csoAddr, uint _tokens) public{
        require(msg.sender == authority);
        csoList[_csoAddr].tokens += _tokens;
    }

    //The charging process
    struct Process{
        address evuAddr;
        address csoAddr;
        uint energyDemand;
        uint chargingTime;
        uint power;
        bool[] schedule;
        uint[] prices;
```

```
        uint csoPrice;
        bool connected;
        bool[] settled; //whether a time-step is settled
        int[] drSignal;
    }


    uint public numCPs; //Control which charging process it is
    mapping (uint => Process) public processes;  //Connects a charging process to a charging process ID, cpID

    //1. AUTHORISATION: called by the EVU
    function authorisation(address _csoAddr) public { //request to charge at a charging station
        require(evuList[msg.sender].addr == msg.sender); //Checks that the evu is registered in the system, and is the msg.sender
        require(csoList[_csoAddr].addr == _csoAddr); //Checks that the cso is registered in the system
        require(evuList[msg.sender].tokens > 100*csoList[_csoAddr].price);
        uint cpID = numCPs++; //Create a charging process ID
        Process storage p = processes[cpID];
        p.evuAddr= msg.sender;
        p.csoAddr= _csoAddr;
        p.power= csoList[_csoAddr].power;
        p.csoPrice= csoList[_csoAddr].price;
        p.connected= true;
        emit Authorised(cpID); //Notification sent out that the charging session is authorised with its cpID
    }

    event Authorised(uint cpID);

    //2. SCHEDULING:
    // Data acquisition from the EVU
    function addDemand(uint _cpID, uint _chargingTime, uint _energyDemand ) public{
        Process storage p = processes[_cpID];
        require(msg.sender == p.evuAddr) ; //can only be added by the evu itself
        p.energyDemand= _energyDemand;
        p.chargingTime= _chargingTime;
        emit requestPrices(_cpID, _chargingTime);//event notify ES with charging time and cpID
    }

    event requestPrices(uint cpID, uint chargingTime);

    //Data acquisition on prices from the ES
    function addPrices(uint[] memory _prices, uint _cpID) public{
```

```
        require(msg.sender == es); //Can only be added by the ES itself
        require (_prices.length == processes[_cpID].chargingTime); //have to add prices for correct charging time
        Process storage p = processes[_cpID];
        p.prices = _prices;
        emit createSchedule(_cpID);
        //event; notify CSO to schedule
    }

    event createSchedule(uint cpID);

    //Creating the schedule
    function scheduling(uint _cpID) public{
        Process storage p = processes[_cpID]; //STORAGE?
        require((p.energyDemand != 0) && (p.prices.length != 0)); //Cannot create schedule without necessary data
        p.schedule = new bool[](p.chargingTime);
        p.settled = new bool[](p.chargingTime);
        p.drSignal = new int[](p.chargingTime);
        for (uint i = 0; i<p.chargingTime; i++){
            p.schedule[i] = true;
            p.settled[i] = false;
            p.drSignal[i] = 0;
            }
        if (p.chargingTime*p.power > p.energyDemand){ //If more charging time than needed for demand
            uint t = p.chargingTime- p.energyDemand/p.power; //t=hours not charging (rounded up)
            uint[] memory priceOrder = order_sort_array(p.prices);
                for (uint i = 0; i<t; i++){
                    uint temp = priceOrder[i];
                    p.schedule[temp] = false;
                }
        }
    }

    //3. CONTROL:
    function control(uint _cpID, uint time) public{
        Process storage p = processes[_cpID];
        require(msg.sender == p.csoAddr); //controlled by the cso
        checkDRAndUpdate(_cpID, time);
        if ((p.connected == true ) && (p.schedule[time] == true)){
            evuList[p.evuAddr].SOC += p.power;
        }
        if ((p.connected == false) && (p.schedule[time] == true)){
            p.schedule[time] = false; //if not connected, but schedule = true, update schedule to false.
        }

```

```

    }
    event AcceptedDR(uint _cpID, uint time);

    function addDRsignal(uint _cpID, uint time, int signal) public{
        require(msg.sender == dso);
        Process storage p = processes[_cpID];
        if ((signal == 1) || (signal == -1)){
           p.drSignal[time] = signal;
        }
    }

    //4. PAYMENT:
    function payment(uint _cpID, uint time) public{
        Process storage p = processes[_cpID];
        if ((p.connected == true ) && (p.schedule[time] == true) && (p.settled[time] == false)){ //only occur if rules are met
            payES(p.evuAddr, p.prices[time]*p.power);
        }
        if (p.drSignal[time]==2){
            payDR(p.evuAddr);
        }
        payCSO(p.evuAddr,p.csoAddr,p.csoPrice);
        //if responded to dr - dso pays.
        p.settled[time] = true;
        if (time == p.chargingTime-1) { //disconnect if charging is finished
            p.connected = false;
        }
    }

    function disconnect(uint _cpID) public {
        Process storage p = processes[_cpID];
        require(msg.sender == p.evuAddr); //only the evu can disconnect before charging schedule is finished
        p.connected = false;
    }

    //Internal functions:
    //Private means it can only be used by the functions in the contract, where rules are followed.
    function payCSO(address _sender, address _receiver, uint amount) private{
        require((amount <= evuList[_sender].tokens), "Insufficient balance.");
        evuList[_sender].tokens -= amount;//subtract amount from sender
        csoList[_receiver].tokens +=amount;  //add amount to receiver
    }

     function payES(address _sender, uint amount) private{ //amount positive if sending gtokens, negative if receiving tokens
        require(amount <= evuList[_sender].tokens);
```

```
        evuList[_sender].tokens -= amount;
    }

    function payDR(address _receiver) private{
        evuList[_receiver].tokens += drPrice;
    }

    function checkDRAndUpdate(uint _cpID, uint time) private{
        Process storage p = processes[_cpID];
        while ((p.drSignal[time] == 1)&&(p.schedule[time]==false)){
    for(uint i=time+1; i<p.chargingTime; i++){
                  if(p.schedule[i] == true){
                        p.schedule[i] = false;
                        p.schedule[time] = true;
                      p.drSignal[time] = 2;
                        emit AcceptedDR(_cpID, time);
        break;
                  }
             }
  }
  while ((p.drSignal[time] == -1)&&(p.schedule[time]==true)){
    for(uint i=time+1; i<p.chargingTime; i++){
                  if(p.schedule[i] == false){
                        p.schedule[i] = true;
                        p.schedule[time] = false;
                        p.drSignal[time] = 2;
                        emit AcceptedDR(_cpID, time);
        break;
                  }
              }
        }
    }


    function order_sort_array(uint[] memory arr) private pure returns (uint[] memory) {
        uint l = arr.length;
        uint[] memory order = new uint[](l);
        for(uint i = 0; i < l; i++) {
            order[i] = i; }
        for(uint i = 0; i < l; i++) {
            for(uint j = i+1; j < l ;j++) {
                if(arr[i] < arr[j]) {
                    uint temp = arr[i];
                    arr[i] = arr[j];
                    arr[j] = temp;
                    uint temp2 = order[i];
                    order[i] = order[j];
                    order[j] = temp2;
```

```
                }
            }
        }
        return order;
    }

    function getOrder(uint _cpID) public view returns (uint[] memory) {
        return(order_sort_array(processes[_cpID].prices));
    }

    //Functions for displaying simulation results:
    function getProcessInfo(uint _cpID) public view returns( address, address, uint, uint, uint, bool[] memory , uint[] memory, uint, bool,  bool[] memory, int[] memory){
        Process memory p = processes[_cpID];
        return (p.evuAddr, p.csoAddr, p.energyDemand, p.chargingTime, p.power, p.schedule,p.prices,p.csoPrice, p.connected, p.settled, p.drSignal);
    }

    function getEvuBalance(address _evu) public view returns(uint){
        return (evuList[_evu].tokens);
    }
     function getSOC(address _evu) public view returns(uint){
        return (evuList[_evu].SOC);
    }
    function getCsoBalance(address _cso) public view returns(uint){
        return (csoList[_cso].tokens);
    }

    function getAddressAuth() public view returns(address, address, address){
  return(authority, dso, es);}

    function getCpID() public view returns(uint){
        return (numCPs-1);
    }
}
```

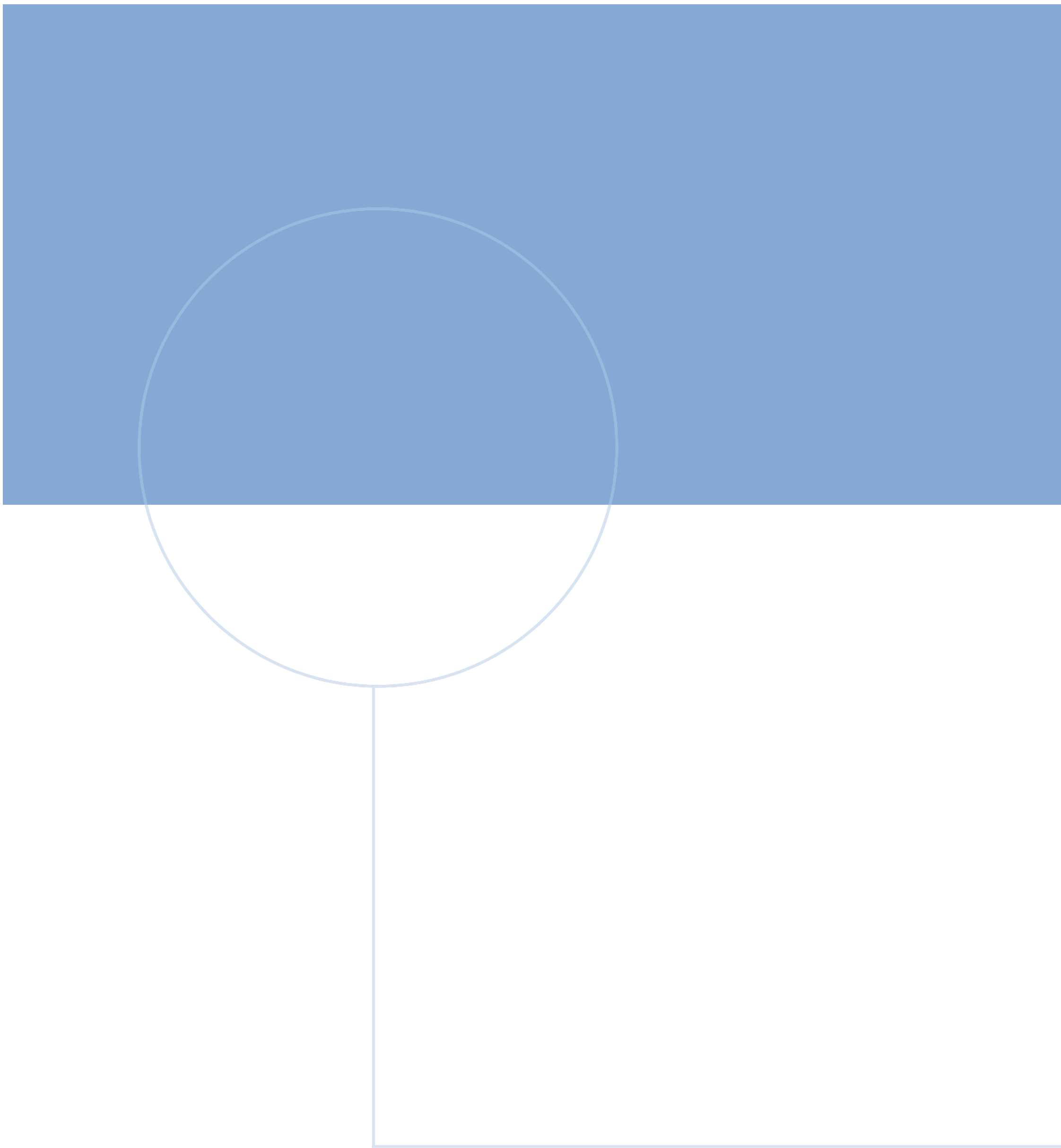
Appendix B

Python script

```python
from web3 import Web3, HTTPProvider
import json

web3 = Web3(HTTPProvider('http://localhost:7545'))#Connect to the blockchain

##Open, read and close JSON file for the related solidity contract:
jsonFile=open('/Users/minaryssdal/master/build/contracts/evcharging.json','r') #where the file was deplyued
values = json.load(jsonFile)
jsonFile.close()

abi = values['abi']
address =  input("Contract address:")#Created when deploying the contract to Ethereum

EVcharging = web3.eth.contract(address, abi=abi) #To interact with the solidity contract

#Values:
power = 5
csoPrice = 5
dsoPrice = 30
energyDemand = 30
chargingTime = 10
prices = [1, 1, 2, 3, 3, 2, 2, 1, 1, 1]
startTokens = 1000

#Connect actors to blockchain nodes:
authority =web3.eth.accounts[0]
dso =web3.eth.accounts[0]
evu = web3.eth.accounts[1]
cso =web3.eth.accounts[2]
```

```python
es = web3.eth.accounts[3]

#Set the actors
EVcharging.transact({'from':authority}).setDSO(dso, dsoPrice)
EVcharging.transact({'from':authority}).setES(es)

EVcharging.functions.newEVU(evu).transact({'from':authority})
EVcharging.transact({'from':authority}).changeTokensEvu(evu, startTokens)

EVcharging.transact({'from':authority}).newCSO(cso, power, csoPrice)
EVcharging.transact({'from':authority}).changeTokensCso(cso, 0)

print(EVcharging.call().getAddressAuth())

evBalance = EVcharging.call().getEvuBalance(evu)

EVcharging.transact({'from':evu}).authorisation(cso)
print('State after authorised:')
cpID =EVcharging.call().getCpID()
print(cpID)
print(EVcharging.call().getProcessInfo(cpID))

EVcharging.transact({'from':evu}).addDemand(cpID, chargingTime, energyDemand)
print('State afterdemand:')
print(EVcharging.call().getProcessInfo(cpID))

EVcharging.transact({'from':es}).addPrices(prices, cpID)
print('State after prices:')
print(EVcharging.call().getProcessInfo(cpID))

EVcharging.transact({'from':cso}).scheduling(cpID)

print('State after schedule:')
print(EVcharging.call().getProcessInfo(cpID))

#DSO adds DR signals
EVcharging.transact({'from':dso}).addDRsignal(cpID, 1, -1)
EVcharging.transact({'from':dso}).addDRsignal(cpID, 4, 1)

#Save results
EvuBalance = [0 for n in range(chargingTime)]
CsoBalance = [0 for n in range(chargingTime)]
SOC = [0 for n in range(chargingTime)]

#Iterate
for t in range(0, chargingTime):
    EVcharging.transact({'from':cso}).control(cpID,t)
    EVcharging.transact({'from':cso}).payment(cpID,t)
    print('Time: ', t)
```

```
    EvuBalance[t] =EVcharging.call().getEvuBalance(evu)
    CsoBalance[t]=EVcharging.call().getCsoBalance(cso)
    SOC[t]=EVcharging.call().getSOC(evu)
    print(EvuBalance[t])
    print(CsoBalance[t])
    print(SOC[t])
    print(EVcharging.call().getProcessInfo(cpID))
```



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