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Faculty of electrical engineering

Department of Economics, Management and Humanities

Diploma Thesis

Price of charging definition supported by Blockchain application

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ZADÁNÍ DIPLOMOVÉ PRÁCE

I. OSOBNÍ A STUDIJNÍ ÚDAJE

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II. ÚDAJE K DIPLOMOVÉ PRÁCI

Název diplomové práce:

Price of charging eletric vehicles definition supported by blockchain application

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Price of charging eletric vehicles definition supported by blockchain application

Pokyny pro vypracování:

1. Blockchain, technology description
What is blockchain, today´s use, it´s history, creator, how did blockchain got to the awareness of people, computing difficulty, it´s energy consumption, scalability and flexibility
2. Application of blockchain nowadays in modern industry and it´s benefits, analysis of current projects connected to this technology, proofs of work
Potential outside of cryptocurrency world, first projects and applications in medicine, automotive, logistic, energetics, etc.
3. Current electromobility
Limitations in current electromobility sector, emission restrictions, charging issues, concepts of sustainability, costs of charging stations
4. Future electromobility
Current development description, advantages of blockchain implementation, sustainability in upcoming growth of e-vehicles operated in europe, grid stabilization using in-car batteries
5. Determination of the e-vehicle charging prices
Current price formulas of the charging station, price reduction in cases of implementing proper it solution, different approach of the charging (not a load but a profit to a grid)

Seznam doporučené literatury:

BHEEMAIAH, Kariappa. The blockchain alternative: rethinking macroeconomic policy and economic theory. New York, NY: Apress, [2017]. ISBN 978-1-4842-2674-2.
TANG, Wanrong. Optimal charging control of electric vehicles in smart grids. New York, NY: Springer Science+Business Media, 2016. ISBN 9783319458618.

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Declaration

I declare that the work presented in this thesis was developed independently and that I have listed all relevant sources of information used within according to the guidelines on observing ethical principles in preparation of university theses.

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Signature

Abstract

This thesis explores emerging opportunities at the intersection of energy and automotive industries, enabled by Blockchain technology as a tool for digital transfer of value. The thesis offers a description of Blockchain technology and its commercial usage also in electric mobility. To outline a specific use case, the formula for price of charging is defined for a situation of an electric vehicle equipped with bi-directional charging, enabling it to provide ancillary grid services for which the owner of the electric vehicle is rewarded. This revenue is then expanded to account for externalities such as the battery degradation, which play crucial role in the calculations. Other nascent benefits of implementing Blockchain are also indicated.

Keywords

Blockchain, V2G, charging price, electric vehicle, battery degradation, ancillary services, bi-directional energy flow, smart charging

Content

1. Introduction

We are living in a world increasingly reliant on technology. Progress of development in every industry has accelerated in the last decades. A fitting illustration is the difference in technology between years 1998 and 2018. 20 years ago, there were not many people that were using smart phones, electric cars or wireless gadgets. 40 years ago, almost no one was using internet or even owning a computer. On the other hand, majority of people in developed countries today cannot imagine living without such technology.

Since the beginning of the 20th century, people are used to using electricity, from basic purposes like lighting a lamp to advanced ones like charging an electric vehicle or solving complex mathematic equations, first in mainframe computers and today in their pocket. Increasing expectations of customers and citizens require businesses and service providers to keep pace with technology progress in order to stay competitive and relevant.

Automotive and energy industries undergo profound change illustrated by transformative investment in developing electric vehicles, battery systems, charging stations or refining markets underpinning distribution and trading of electricity. But are these solutions being developed with resilience, sustainability, and competitiveness in mind? Aren't there other possibilities? Which solution is least expensive but also brings most of advantages? How much does it cost for the final customer? Which IT solution will support interaction between the customer and multiple service companies, and how?

A number of constraints manifests itself in the context of electro mobility, charging of electric vehicles, charging infrastructure, grid optimization, consequences of an increasing number of electric vehicles etc. To account for these facts, some precautions must be considered. Increasing the number of electric vehicles in operation can have a negative effect on the local grid systems when the vehicles connected to their chargers are being charged individually, without coordination. Fortunately, there are ways how to mitigate such negative effect. An electric vehicle does not have to merely act as a consumer, but can also support the balance of the grid utilizing its onboard battery which has major potential thanks to its energy capacity. Its supportive actions can help with grid Ancillary Services such as a Peak Load Shaving, Frequency Regulation or Net Load Shaping.

To motivate owners and drivers, the electric vehicle can be rewarded with, for instance, lower final price of charging. This of course is not possible without considering certain issues and limitations. Providing services with active discharge from the onboard battery negatively affects the battery life and can limit the owner of the EV (Electric Vehicle). The revenue must be therefore for the customer more valuable than the impact on the onboard battery system. The definition of revenue and price of charging is shown in this thesis with a model of rewarding the vehicle per grid service event or via battery degradation costs.

This thesis explores the role of Blockchain when considering a vehicle connected to the grid and providing Ancillary Services. Some of the features of Blockchain technology might help with processing the transactions, calculating revenues, storing the data, providing transparent records of all actions during and after the charging. It should be noted that Blockchain itself is not an element that can influence the price of charging directly. Blockchain technology can augment other technologies like Smart Metering, Artificial Intelligence and Internet of Things, providing solid transaction infrastructure, supporting interactions of Grid System Operators, retail service providers and final customers (EV owners).

Some of the cases of Blockchain implementation are also described in this thesis to illustrate the potential and applications of this technology in meaningful areas of energy and automotive sectors. In some cases in the future, Blockchain could become indispensable.

2. Blockchain technology

The term “Blockchain” (originally “block chain”) is entering more and more into public consciousness in recent years and nearly everyone has heard at least something about Blockchain. However, most of the listeners connect this term (rightfully) to a virtual cryptocurrency called “Bitcoin”. Bitcoin is a peer-to-peer version of electronic cash which allows one party to send payment to another party without any intermediary. This means that no centralized third party (like a bank or a mint) is needed to confirm executed transactions.

Blockchain itself is a technology platform concept on which Bitcoin and other cryptocurrencies are being built.

Blockchain implementations are a “software” which was developed to serve as a transparent transaction database that contains every transaction in the system ever executed. It is distributed over a computer network, with each computer storing an identical copy of the same database file, sometimes called distributed ledger technology. So-called “miners[1]” support the network and in doing so are being rewarded. Detailed explanation of this technology will be described in this chapter.

[1] Owners of any suitable hardware that provides computational power within blockchain.

2.1 Technical description

Bitcoin was the first cryptocurrency that successfully applied Blockchain technology. Because of that, everything about bitcoin and Blockchain itself is described in numerous internet resources. One of the reasons is that the source code was publicly shared by the Bitcoin creator - Satoshi Nakamoto. Sharing the code gave people the opportunity to analyze the code into greatest detail. However, it also opened a gate for anyone (including hackers) to look for a bug or a hidden “backdoor”[2] in the code. Despite this opportunity, most attempts to find a bug failed and only one known incident happened in 2010. The issue was fixed within couple of days, with no damage done, by releasing of an updated version of the bitcoin protocol [1]. This was the only major security flaw and since then, no one ever violated or hacked the core of the Bitcoin Blockchain [2] – a testament to the resilience of the solution. Future development lead to a market capitalization of Bitcoin in the range of 60-240 billion dollars and volume of transaction processed within 24hours in the range of 5-44 billion USD [3].

Blockchain key features include [2]:

- Transparency,
- security,
- decentralization,
- programmability,
- immutability.

These features ensure a correct, stable and well-known behavior of the system. All of these aspects are explored in the description of this technology. Bitcoin is the best example to describe the technical implementation of the Blockchain core technology, even though it has no connection to the electricity or automotive industries.

Later chapters of this thesis will concentrate more on the subject of Blockchain implementation for electricity markets, commercial usage, vehicle charging and other energy-related industries.

[2] A backdoor is a means to access a computer system or encrypted data that bypasses the system's customary security mechanisms [47].

2.2 Architecture

A payment process can well describe the flow of the transaction being transferred from one party to another in the virtual world via Blockchain. The transaction is processed in a peer-to-peer fashion, meaning without any central trusted authority which would confirm the transaction.

This process is autonomous, decentralized and based on Blockchain technology which is backed by computer hardware, mathematics and cryptography. This solution also prevents double-spending problem, using timestamping transactions by “hashing”[3] them into one ongoing chain of blocks. More details about hashing, cryptography, security itself and double-spending prevention will be described in later paragraphs.

[3] A Hash or so-called hash function is any algorithm that maps data of arbitrary length to data of a fixed length. The values returned by a hash function are called hash values, hash codes, hash sums, checksums or simply hashes. Recent development of internet payment networks and digital money, such as Bitcoin, also uses a form of 'hashing' for checksums, and has brought additional attention to the term [2].

Picture of Blockchain transaction process:

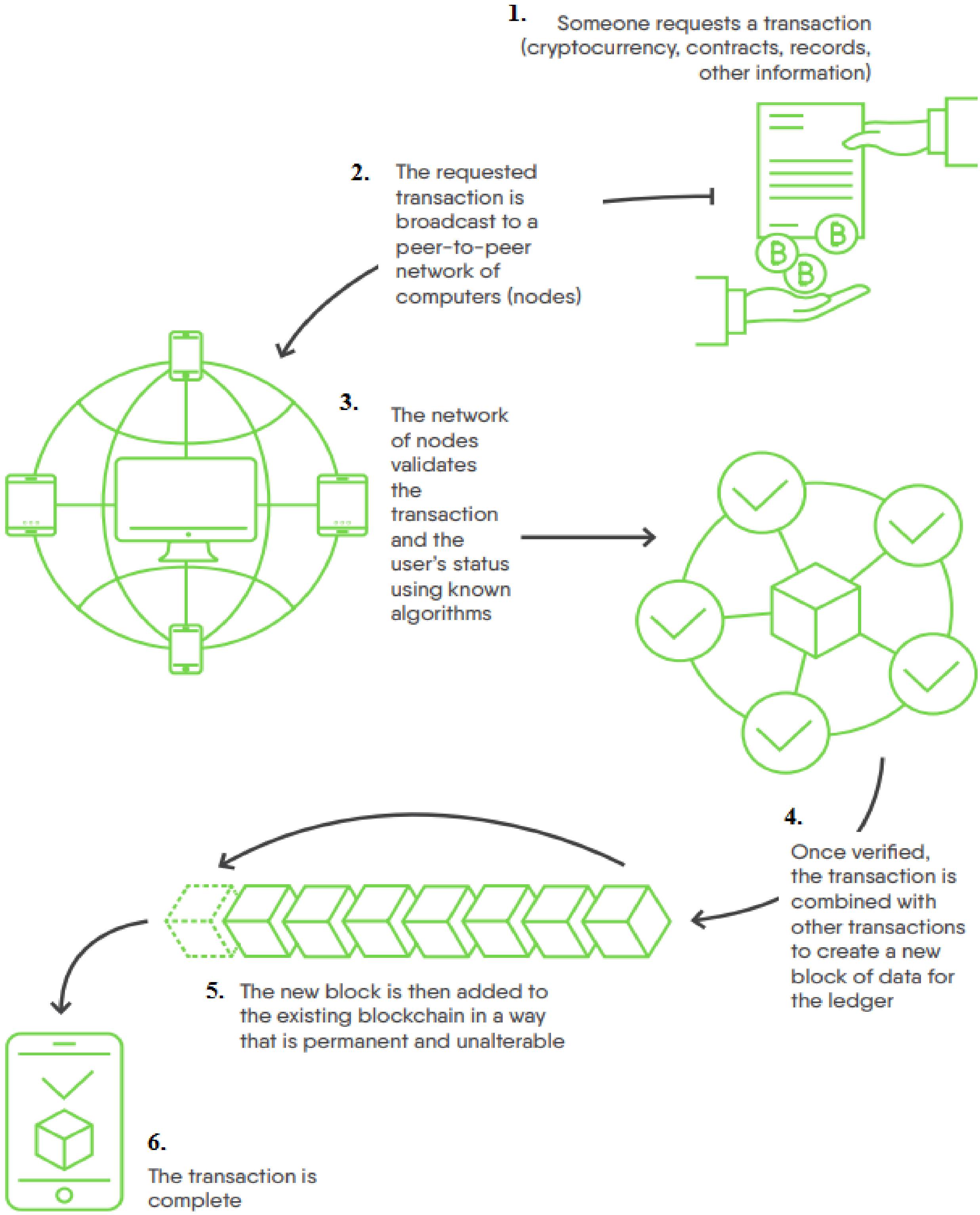

Figure 1. – Blockchain transaction process [4]

In the picture above is shown the lifecycle of a transaction. There are several preconditions which must be fulfilled.

User, who can be a person or a machine, must be connected to the Blockchain network via either a pre-programmed mobile or computer interface. Another precondition is that the user application must follow the syntax of the Blockchain code (which should be already implemented in the applications for users). An example of an application is the mobile wallet which is designed to provide features like receiving or sending transactions and showing the balance within a virtual account.

Main parts in the model are:

- Users,
- nodes,
- blocks.

These parts combined create a network without which the Blockchain ecosystem would not work. Users expect that if they send a transaction to another user, it will be successfully executed thanks to the underlying IT solution. There is an extensive logic determining how the transaction is processed, which will be partly described in the thesis later, subject to the scope of the thesis. The nodes, instances of the Bitcoin software operating on independent computers within the distributed network, are connected to the users and vice versa. The blocks, consisting of sets of chronologically ordered, verified transactions, are continuously created, distributed, and stored by the nodes.

2.3 Users

Before an action happens in the core of the Blockchain network, someone has to trigger a “transaction” request. This kind of request can be a contract change, record, cryptocurrency transaction or transfer of any other information. The start of this process could be triggered either by person or a machine (computer or any other device connected to the Blockchain).

Access right of every user is defined by a pair of cryptographic keys: Public Key, which is known to all members of the Blockchain system and is necessary for identification, and Private Key, which is kept secret and is used for encryption and authentication of the information.

Private Key grants user ownership of his cryptocurrency funds assigned to a given address. Blockchain wallets can automatically generate and store the private keys of the owner. When a transaction is initiated from this wallet, software signs the transaction with the user´s private key proving he is authorized in the network to operate with relevant funds assigned to the cryptocurrency address.

This process of securing addresses by using private and public keys is based on asymmetric cryptography, whose description is beyond the scope of this work.

2.4 Nodes

In a Blockchain network, every participating computer which joins this network is called a node. These nodes are individual parts of a larger data structure which forms the infrastructure of Blockchain. The node can be described as an electronic device which is capable of establishing connection to the internet and has an IP address[4] assigned. The purpose of the node is to compile all software instructions which might be for example verifications of a transaction. The nodes can store, preserve and broadcast all data of Blockchain. In essence, Blockchain is based on all nodes connected to the network which communicate with each other simultaneously.

There are two types of nodes [2]:

1. Full nodes
   - Which store the full history of actions already executed (For example in the Bitcoin network it would be every single transaction that has occurred on Blockchain).
2. Light nodes
   - These nodes cover only a part of the Blockchain history (In the Bitcoin network it could be a partial list of transactions executed over a period of time, e.g. last month),
   - Despite the fact that light nodes cover only part of the history, they are commonly linked to the full nodes. This helps to make sure these lists are accurate.

Both types of nodes can be online or offline. The only difference is that once the offline node gets online again, it must simply update its history since the node went offline.

The purpose of the nodes is to preserve the Blockchain history. It can be established by only one single full node connected to the network. However, in Blockchain based cryptocurrencies like Bitcoin, there are several thousands of online running nodes at any given time, which makes the technology extremely resilient to hacks, power failures or internet network crashes. Attacker simply cannot destroy or manipulate all nodes at once, for reasons which will be described later.

But what incentives are offered to owners of the nodes to provide their memory and computing power? In the case of cryptocurrencies, full nodes are being run by cryptocurrency enthusiasts and users who want to make sure that the current network runs correctly. Owning a full node also gives the user certainty that no corrupted transactions or double spending is executed. Other entities which might run the full nodes are parties that benefit from it. It could be for example ICO (Initial Coins Offering) entities that let people trade cryptocurrencies, or Pools which provide users with the possibility to join and “mine[5]” the cryptocurrency with their hardware resources combined.

[4] An Internet Protocol address (IP address) is a numerical label assigned to each device connected to a computer network that uses the Internet Protocol for communication [1].
[5] Mining in conjunction with cryptocurrencies is the process of adding transaction records to blockchain. It is performed by high-powered computers that solve complex and very difficult math problems (puzzles).

Nodes are operating without any central authority following a basic consensus rules, creating a peer-to-peer network.

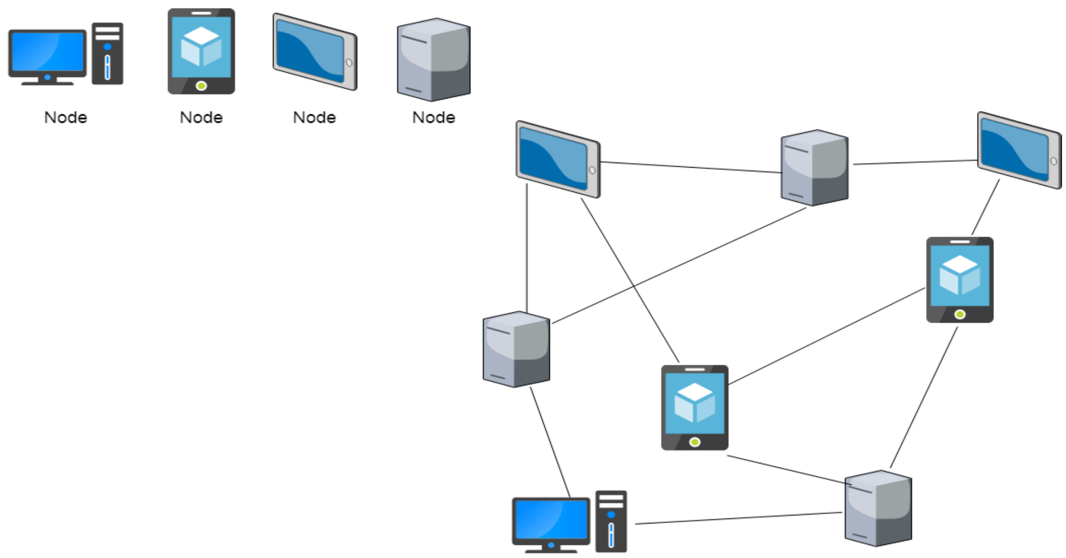

Figure 2. – Visual example of network nodes

Nodes in the network also play a very important role in case of verification of every transaction executed. Transactions are broadcasted to a peer-to-peer network of nodes. The network then verifies the transaction attaching a unique hash to it. Every electronic device connected to the grid can act as a node when following the network rules. It can be for example also an electric vehicle, power plant, smart meter or household itself.

2.5 Blocks

The main building stone of the Blockchain are the blocks on which is the whole technology based. When making a transaction in Bitcoin network, the transaction isn´t added to the Blockchain right away. Records of the transactions are first verified by nodes and then collected to one transaction list / ledger element - called a block.

Blocks can be considered as individual pages of records. After one "page" is full and no other records can be added, another one must be created, and both pages are being organized into a linear sequence known as "block-chain", with the second page containing a summary reference to the previous page. Because of this structure, data is stored in Blockchain permanently and immutably. When a block is securely and cryptographically chained to the other block, data in previous block can never be changed again (entire chain would break). These data (in case of Bitcoin) are public, and everyone can see them. This feature provides a secure network where no one can tamper with already recorded information.

2.6 Consensus mechanism

The consensus protocol[6] is the most important aspect of Blockchain technology. Protocols create irrefutable system of agreement among various devices (nodes) in a distributed network whilst preventing any exploitation of the system. Blockchain consensus protocols are what keeps all nodes in the network synchronized and linked to each other while answering the question: how do we all agree on what the truth is?

Anyone can submit any information to be stored onto a public Blockchain and therefore it is important to have a process of review and confirmation, in the form of a consensus about whether to add that information. When the consensus is reached, the nodes agree on the same state of Blockchain, in a sense making it a self-auditing ecosystem.

This is a crucial aspect of the technology, carrying out two key functions. Firstly, consensus protocols allow a Blockchain to be updated, while ensuring that every block in the chain is true as well as keeping participants incentivized. Secondly, it prevents any single entity from controlling or derailing the whole Blockchain system. The aim of consensus rules is to guarantee a single chain is used and followed [5].

2.6.1 Consensus protocol rules

In such a complex system as Blockchain is, the set of specific rules must be respected by the participants (nodes) on the network to ensure that data in each block are processed correctly and without any damage. There could be also an intention from one party to behave to his own advantage and not according to the consensus rules.

For example, in case of cryptocurrency trading, when someone tries to spend some virtual coins and then reverse the transaction by broadcasting their own version of Blockchain with the transaction excluded (known as double spending). Because the Blockchain technology does not rely on a central authority or a third party, participants would not have the knowledge of which version of the records is valid, unless the consensus identifies the accepted set of transactions.

Consensus protocol rules must be followed. The key requirement is to achieve a consensus to ensure that nodes in the network accept only a single data stream, even if some of the nodes are unavailable or being unreliable in any way. Thus, every Blockchain must have its rules to protect the network against attacks. Consensus protocols incentivize participants who are maintaining a Blockchain by providing them with rewards. These rewards come in the form of

[6] A set of rules describing how the communication and transmitting of data between electronic devices, such as nodes, should work. These rules need to be defined before any data is sent, detailing how the information will be structured and how each device will send or receive it [5].

virtual currencies, coins or tokens, leading to an economic competition to confirm a new block in a chain.

Multiple models of consensus can be applied according to the objectives and goals of each Blockchain solution. These methods vary depending on the Blockchain within which the blocks are being validated. Different solutions fit different situations.

Consensus protocols are key features allowing the Blockchain to exist and function in a decentralized manner. The Blockchain ledger provides all information history and ensures that these data are stored safely, accurately, and protected against tampering by anyone.

2.6.2 Models

Crucial aspects of the Blockchain are speed, usability and security. Bitcoin's creator/s with a pseudonym Satoshi Nakamoto began the era of Blockchain solutions based on the "proof of work" consensus. However, every solution has its own pros and cons. In the Bitcoin network for example, the transaction processing capacity is estimated between 3.3 and 7 transactions per second. And because of the rising number of active users, the transaction throughput could be a crucial issue. For a comparison VISA, the payment cards company, says they can for example process 15 000 - 20 000 transactions per second [5]. But that does not mean there are no less centralized and more energy-efficient consensus algorithms [2].

There are main 3 types of Consensus models that are practically explored and therefore within the scope of this thesis. These models have been applied in certain industries and have shown its pertinence and capability. Therefore there is a very significant potential in application for example in wholesale energy trading, electric vehicle charging, retail electricity markets etc.

1. **Proof of Work**

PoW (The Proof of Work) consensus mechanism is most often associated with the current Blockchain technology that relies on so-called "miners". Miners must solve difficult cryptographic puzzles (finding the right hash of the block header) for the right to add the next block in the chain. After solving the puzzle, the solution is forwarded to other nodes in the network and needs verification from them before being accepted to their respective copies of the ledger. Miners are incentivized to compete in mining new cryptocurrencies by receiving a reward. Current Blockchain systems operating under PoW are for example Bitcoin, Ethereum, Litecoin, Monero and many others. Using a PoW-based Blockchain becomes very energy-intensive as the network grows. It is also associated with much slower transaction speed [4].

2. **Proof of Stake**

PoS (Proof of Stake) is not as energy intensive as the PoW consensus. The main reason is that instead of solving difficult cryptographic puzzles (meaning there is therefore no mining process and competing users), the system distributes stake transition rights across the network, depending on the balance of each account. The more stake every participant owns, the higher is the probability of being picked as the validator of each set of transactions. There are different PoS algorithms in regard to the architecture and also validator rewarding systems. This approach decreases the complexity of the verification process so its operation costs can be reduced [4].

3. **Proof of Authority**

In the PoA (Proof of Authority) consensus, validators are determined before any validation is being processed. These authorities must be trustworthy and uncompromised. The process is automated and does not require validators to be constantly monitoring their devices. The PoA consensus might be considered to be a less decentralized algorithm compared to PoW and PoS. That means it might be also more prone to attacks than the other consensuses but due to the decreased number and complexity of choosing specific validator, it is more efficient in processing transactions. The speed in some implementations is approximately 3-4 seconds in processing a whole block of transactions.
This consensus is being mostly used in private or semi-permissioned Blockchains.

2.7 Permission models

Apart from different consensus mechanisms, the type of Blockchains can be also distinguished one from another by its permission models. The choice depends on the Blockchain software author, business model, industry, or region in which is Blockchain supposed to be applied.

The permission model defines who can use the Blockchain network. In case the network allows anyone to use it without any restriction/permission (as it is in the Bitcoin's network) the Blockchain is called Public. In a public Blockchain, no one has control over the network itself, the solution is decentralized. Also the data cannot be changed once recorded in the chain. On the opposite side of the spectrum there is a Private Blockchain, which is accessible only for specific users. Therefore to access the network the user has to obtain a permission first from the pool or association of the system providers (or following the special instructions for getting the access right).

Private Blockchain models will most likely select the PoA or PoS consensus, since the participants in the system are known. Private Blockchain is therefore sometimes called "enterprise" Blockchain. One of the examples of usage of a private Blockchain is in the healthcare industry. Only patients and doctors are allowed to access the network.

It is important to mention that private and public models can be combined. Users can have rights to only read the data but not to write them etc.

	PUBLIC	PRIVATE
Access right	Open, anyone can write/read	Restricted "Know Your Customer" (KYC) policy
Validation	Permissionless, unknown validators (risk of "Sybil attack")	Permissioned, known validators (can ban who misbehave)
Speed	Slow clearing, fast settlement	Fast, high performances. Settlement might be slow depending on the process
Security	Immutable record	Reversible, can edit and change the history
Identity	Anonymous/pseudonymous	Known (KYC rules)
Asset	Native digital token used for mining reward	Customisable type of asset
Cost	Energy, OPEX	Development cost, CAPEX
Consensus	Proof of Work, possible Proof of Stake in the future	Proof of Stake, Delegated Proof of Stake, Proof of Elapsed Time, Byzantine Fault Tolerance algorithms

Table 1. – Blockchain variety of technical and governance Characteristics [4]

3. Blockchain application in electricity sector

At first, Blockchain technology was applied only in money transfer, cryptocurrencies and trading, but gradually it finds additional suitable industries in which it is being applied. One of the reasons is that the trading and cryptocurrencies proved its potential in real-life environment. For example the Bitcoin´s Blockchain has been operational for more than 10 years (at the time of writing this thesis) without any significant issues, bugs or a single outage.

Blockchain technology can be integrated into several areas like smart contracts (contractual activities that can be automated and executed without any human interactions), financial services (e.g. distributed ledgers for banks), supply chain (tracing services), health care (medical records), IoT (Internet of Things), gaming industry etc.

The first experiments in applying Blockchain were only in a form of a POC (Proof of Concept) and not commercially used. However, recent development proved that some of these POCs fulfilled the expectations and are now being transformed to a fully operational state. The usage is now often limited by the scalability of the solution which might be a crucial aspect when analyzing the possibility and efficiency of applications of Blockchain in business models. This section will describe some of the current projects which have successfully completed their POC stage and are now being altered and implemented in a wider and increasingly commercial use.

The purpose of this thesis is not to describe all existing or possible solutions and projects but to show the way Blockchain technology is being adopted worldwide in viable solutions and projects. A special section will be dedicated to Blockchain in electro mobility, therefore only projects excluding Blockchain associated with EVs will be mentioned in this section.

3.1 Peer to peer energy trading

This model of trading is defined by the direct trade of users among themselves. It can be applied to a smaller group of users, such as a village or city where several customers have installed any kind of power plant (photovoltaic and wind mostly). These "prosumers" (derived from consumers and producers) at times offtake electricity and in other periods deliver electricity to the grid.

In fact, this type of business now indirectly works through the sale of the electricity produced to the trader who subsequently re-sells it to other customers who use the surplus production to cover their electricity demand. In traditional solutions the electricity sold in this way directly from a customer with solar power plant is being purchased for around 20-24 EUR per MWh [6].

Thanks to the novel IT solutions including Blockchain, there is a possibility to arrange local trading without the need for a third party. The transaction can happen automatically between the pair of customers. For example, the price can be stated based on an agreement of a pair of users, not trader´s. Blockchain can handle the transaction processing, and P2P (Peer-to-Peer) energy community measurement processes that allow transactions to be conducted directly between users. In addition, transaction logs are stored, accessible to all network participants without the possibility to manipulate it. Smart contracts or any other billing method might support the operator of this system to cover the payment process.

The solution requires adequate hardware equipment, which should mainly include an Internet-connected device along with an intelligent metering system, and provides validation between the electrical system and the Blockchain. The meter should record production, export and import. The production could be converted into tokens, which can then be traded in digital currencies or other fiat money. Possible advantages in case of implementing the suitable Blockchain solution [4]:

• Engaging connected users to produce and operate in energy trading system,

• better use of the electricity surplus,

• cost savings to buy and sell el. energy from small PV power plants,

• contribution to Climate Neutrality,

• reducing the workload of operating networks.

Examples of projects

1. One of the first projects is the Brooklyn Micro grid Project. LO3 Energy Company in conjunction with Siemens successfully implemented the pilot project that has been running since 2016. Residents who own solar power plant on the roof can sell surplus energy to their neighbors using peer to peer network. The main advantage of so-called Micro grids is to

reduce the loss of electricity by long-distance transmission. More about this project can be found on the LO3 Energy website [7] [8].

2. The German developer Ponton focuses on its development of trading on the wholesale electricity market. The goal of the Enerchain project is to reduce market access costs, transaction fees, remove entry barriers for smaller businesses and simplify trading with non-standard products. The project takes part in more than 40 energy companies and many other foreign companies (including for example Czech company ČEZ).

Enerchain gives traders anonymous ability to arrange, trade, verify, or confirm P2P business. One of the great advantages in the future could be elimination of needs to report to the regulators and possibility to read all the transfer data directly from the Blockchain database [9].

Enerchain evolved at the end of 2019 into Enerchain Local, which at the time of writing this thesis is being tested in cooperation with Austrian and German utilities [10].

3.2 Emission allowance trading and other certificates

One of the other very interesting possibilities of using a Blockchain is due to one of its main advantages – decentralization and immutability, for example, in the emission allowances trading. The Veridium project [11] came up with the possible application of assigning its tokens to emission allowances issued. Due to its immutability, it is possible to obtain an absolutely transparent overview of how the allowance is handled, where purchased, when and at what price, whether and to who it was sold, etc. This solution can eliminate much of administration, prevent bugs in the system, reduce the cost of the entire trading process and help effectively track and reduce CO2 production [4].

Further use is, for example, in trade with so-called Renewable Energy Certificates (RECs), which makes it possible to trade and track electricity created from renewable sources like wind, biomass, hydropower, solar or geothermal power plants. One of the first projects are Volt Markets [12] and the initiative by SP Group's Singapore Power [13].

Also World Bank´s carbon Markets and Innovation team is developing a "Climate Warehouse ecosystem" to demonstrate the possibility to use Blockchain technology. The reason behind this decision is to connect climate market systems, record status changes, enhance transparency and trust amongst market participants and enable tracking of mitigation outcomes across different systems [14].

3.3 Grid Stabilization

Grid stabilization is a process mandatory for fully functional and resilient delivery of electricity. The operation of the grid changes as it transforms to accommodate an increased number of connected renewables and distributed sources of electricity, which requires new methods of management. Regulating the grid involves frequency balancing and congestion management. A newly available solution is to let the customers and devices with batteries to help solve this issue (such devices could be for example home batteries or electric vehicles). Because of the increased share of distributed energy resources with intermittent output in the grid, these processes are about to become more important in the future.

The relevance of a Blockchain solution in this case is to coordinate large numbers of decentralized energy units with involvement of multiple electricity system actors in front and behind the electricity meter. Blockchain can be used to create a transparent mechanism for receiving bids for flexibility as well as the tracking of the participation of every single user activity in the system. Blockchain can thus be used to aggregate and coordinate decentralized energy resources to securely and reliably manage flows of electricity and information across regions.

The transmission system operator TenneT and storage supplier Sonnen successfully completed a pilot project in Germany in cooperation with IBM which aims to coordinate photovoltaic home storage systems with a grid in a way which assists the power grid.

"TenneT used a virtual power station comprising home storage systems specially provided by Sonnen for this. The Blockchain solution networked in this way was developed by IBM. Tests served to ascertain the extent to which emergency measures such as curtailing wind farms can be reduced in the event of bottlenecks in the power grid. The intelligent charge management of the battery storage systems adapted itself individually to the respective situation in the TenneT grid, the storage batteries either taking in or giving out excess electricity in a matter of seconds, as and when required. [15]*"*

Sonnen batteries were connected to the grid online, providing all necessary technical data about how much capacity can the storage provide and re-dispatch in each region of the constrained grid. If one of these regional bids were accepted by the TenneT, then the batteries were charged with surplus for example from the nearby solar farms. To maintain the equilibrium some other battery had to be discharged simultaneously. This process and every data transition was recorded in the IBM Hyperledger Blockchain. A record of every kilowatt hour stored or discharged was immutably stored and cryptographically secured. This innovative technology enables decentralized data exchange while ensuring all flexible units are coordinated with the DSOs (Distributed System Operators).

The Hyperledger Fabric Blockchain software source code is hosted by the Linux Foundation. Its implementation ensures high level of transparency and allows transactions to be verified among the market participants [15].

3.4 Energy Data Exchange Platform

All the parties in the electricity value chain would profit from a data exchange and communication platform increasing information accessibility. The exchange would facilitate sharing of metering and all energy transaction data between regulators, generators and suppliers. Using historic data, predictive maintenance and consumption patterns could be used to provide better prediction of the energy flow in the future. This might be useful also for benchmarking, investment decisions and grid management. Blockchain will take a part as trustworthy platform recording real time data about consumption and production, providing this information to multiple authorized parties with different writing or reading access rights. This idea aims to help and facilitate efficiency of current processes in the energy sector and to serve as an option for better real-time operation but also long-term planning and decision making [16].

3.5 Energy Asset register

Another project involving Blockchain in its core technology is in pilot phase by the British transmission grid operator National Grid ESO in cooperation with energy Blockchain tech company Electron. The main goal is to create a shared asset data register.

The "RecorDER" project will involve distribution system operators SP Energy Networks and UK Power Networks, removing the need for a large-scale IT infrastructure or central party hosting the entire system. The project builds a network for operators, aggregators and regulators in which all parties can collaborate using industry-agreed standard shared datasets which do not have to be developed from scratch.

This should improve visibility of available data of all the assets and processes that should help decarbonize and reduce the overall operating costs of the current energy system. This solution could also help in forecasting and planning the usage of the energy assets.

The main advantage of this project is that responsibility of a single register coordinator is eliminated and the system itself act as decentralized entity responsible for all activities inside the network.

The first phase of the project is to map all generation and storage assets with an installed capacity over 1MW using existing network data. Later phases could also cover asset contractual visibility which in future could help also with stabilizing and balancing of involved grids [17].

3.6 Charging vehicle – payment system

One of the earliest and most visible initiatives has been the project "Share & Charge" – a platform and mobile application. In 2016, Innogy in cooperation with Blockchain technology teams, created a peer-to-peer platform allowing "sharing" of charging stations for both the users and the companies who own these stations. Therefore, without the need of a third party, the owner of an electric car can charge his vehicle and pay at the price determined by the station of the owner using the mobile application.

The system is based on the so-called "smart contracts" that run on the Ethereum platform, and the user can virtually pay for the charge of his electric car via the electronic wallet in the application. This whole solution is decentralized and transparent thanks to the Blockchain [18].

The concept and its implementation evolves according to the needs of its stakeholders, reflecting the evolution of standards and regulation.

4. Current electro mobility

Electro mobility is considered as one of the ways to achieve sustainable solution of the future automotive sector. Electric vehicles have been available on the market for years. Due to high purchase price, short driving ranges and insufficient charging infrastructure, there was not much motivation for mainstream customers to buy electric-powered vehicles. That is the main reason the demand was not growing till recent years.

This situation is now changing. Every European automotive company is about to have at least one of the pure electric vehicles on offer in the near future. One of the reasons behind this fact is that automotive companies are being limited by the European rules to decrease the average emissions production of cars to 95g CO_2/km (maximum) by the beginning of the year 2021. Every gram that exceeds this value will incur a penalty of 95€ per car. Multiplied by the produced cars, the potential fee is on the level of 30 billion euros, according to the CEO of Volkswagen, Herbert Diess. Till the year 2030 the emissions should be lowered by another 37,5% [19].

Not only due to this fact the production of the EVs is increasing, and so must be the charging infrastructure. The following chapters will outline some of the limitations and describe the current situation.

4.1 Limitations in electro mobility

There are several limitations that still prevent customers from buying an electric vehicle. The most common one is the fear of the driving distance which the car is capable of reaching on one fully charged battery. It cannot be compared to a combustion diesel engine with a 60l fuel tank and average fuel consumption 6l/100km that can go approximately 1000 km without any stop for refueling. At the time of writing this thesis there is no electric vehicle in serial production that would have similar range. However, some of the newest models have the battery capacity for more than 500km (per fully charged battery) [20].

The issue is gradually evolving from the range being too short to fulfil the needs of the driver, towards insufficient charging infrastructure which lags behind the gas station infrastructure. For example in Europe there is approximately 6000 public charging stations (in the Czech Republic less than 200) [21]. Therefore the best solution for EV owners is to build their own charging station at home, which is of course possible only if living in a house or with access to a shared underground garage space. It gives the owner of the EV an opportunity to fully charge the vehicle for example during the night, when the electricity tariff is better.

This situation shows another disadvantage of the EV. While fueling the tank takes a few seconds, charging an e-vehicle can take multiple hours. There is a remarkable progress in the charging technology so the fastest charging stations can charge the battery up to 80% within 10 - 30 minutes [22]. However, it is still several times longer than traditional fueling, which is a major disadvantage considering the time spent waiting while the vehicle is being charged.

The owner of the EV might be also limited in the choice of providers and the specific charging station. Firstly, not every charging station is suitable for the EV owner´s car, secondly not every charging station provides services such is fast charging. Finally, not all EVs can charge at the same time due to the limited electricity connection infrastructure at certain Charging Points (CPs).

Therefore for sustainable, efficient and user friendly infrastructure some requirements must be fulfilled in the near future. Some of the questions should also be: who should be responsible for building the charging stations? How will be the adaptation of the current grid financed, and how will these issues affect the final price of the EVs charging? Is there any solution that will be convenient for all involved parties? These topics need to be addressed at the same time, and will be explored further in this thesis.

4.2 Charging roaming

There is a significant similarity in vehicle charging and mobile phone roaming of the telecom industry. Because of the relatively young and quite fragmented market, there is a lack of interoperability between different participants within the charging network. No proper system, data transfer and market role definition has been properly set up yet (compared to the telecom industry). Attention has been therefore drawn to enable the owners of the EVs to charge their vehicle at any charging station independent of their usual provider. This concept is referred to as charging roaming and is supposed to be widely accepted in order to provide a suitable environment for future electro mobility in Europe.

E-mobility roaming refers to the situation where the user is capable of charging his vehicle outside of the coverage area of the home network operated by the user's usual Charge Point Operator (CPO).

Cooperation between operators might provide advantage in the form of acceptance of customers of competitors, while also providing flexibility to their own customers. This solution is also more attractive for the current customers who have a wider option in choosing a specific operator [16]. Blockchain solution in this subject plays a significant role and offers an interesting solution which eliminates the roaming constraints.

4.3 Costs of a charging station

The cost of charging stations has decreased in recent years, thanks to the growing number of units sold and of technical companies which are starting to sell the complete EVSE (Electric Vehicle Supply Equipment). The cost of the EV charging stations depends on specific technical requirements, which in turn depend on the underlying reason of the decision to build one.

A charging station, which is supposed to be only used for personal needs, can be bought for 400 - 900€. These models are mostly being sold with a Wi-Fi module that gives the customer better overview of the charging process online. This home solution is not used for commercial use and does not have any other specific functions [23].

However, to convince people to buy an electric vehicle the public charging infrastructure must be widely accessible, and the charging time must be as low as possible. To achieve that, fast charging infrastructure must be built and available for the owners of the EV. Until fast charging is widely available, customers will still be reluctant to buy their own BEV.

Public Charging points can be divided into two groups according to the type of current used. For the fast charging, direct current is being used, which can significantly reduce the time needed to charge the battery.

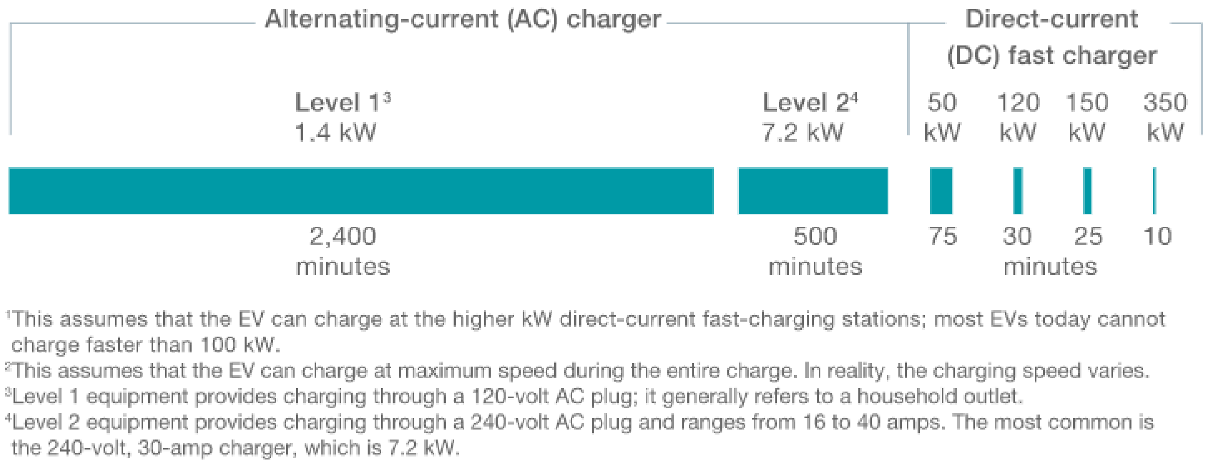

Figure 3. – Different type of charges and time to ”fill-up” the 60kWh battery [24]

Building a CP for commercial use is therefore mostly dependent on the energy demand. The more peak capacity needed, the more expensive will the station be.

The final price for building the station is composed of:

- Charging station hardware,
- electric materials,
- other material,
- electrician labor,
- other labor,
- mobilization,
- permitting.

The price of the charger which consists of all necessary elements starts from 2000$ [22]. This price includes only the initial investment and installation. Once in operation, fixed and variable costs in order to provide charging services to the customers can also include:

- Space rental,
- cost of energy,
- demand charges,
- license permission,
- internet connectivity,
- tax,
- other fees (registration, transaction etc.).

The price of the charger mostly depends on its peak capacity.

To satisfy the needs of the customer, faster charging points must be available at public roads. However, building a DCFC (Direct-Current Fast Charger) might not be profitable due to the variability of the high fees per demand charges.

4.4 Price of charging

The main purpose of this thesis is to define the formula for final price of charging. There are several options and cases how to formulate the price which will be described in detail in Paragraph 6. The price of charging at home is commonly known or can be easily defined according to the electricity price of a given electricity provider.

Electricity providers often offer special tariffs enabling the opportunity to charge EV with a different, typically lower, electricity price while charging at a specific time (mostly during the night).

Calculating the price of charging in commercial use is based on multiple economic models considering the present value of the project, internal rate of return, return on investment, residual cash flows etc.

However, some of the public locations provide charging services for free in order to satisfy their customers (such as supermarkets) or to enable such services to employees. Considering these options, operational costs of an EV can be limited, enabling a way how to motivate the drivers to buy an electric vehicle instead of a combustion engine one.

5. Future electro mobility

Extrapolating from the topics described previously, innovation in electro mobility should solve the known constraints which are limiting the current EV owners. As a customer I want to charge my vehicle whenever needed, without any significant waiting time. Another reason for a switch to electric vehicles is caused by perception of combustion engines as being “not environment friendly”, because of emitting nitrogen oxides, particulate matter such as soot, carbon monoxide and mainly discussed carbon dioxide, so called “greenhouse gas”. Traveling from one point to another using an EV does not damage the local environment compared to vehicles with a combustion engine. In places where the concentration of combustion vehicles is higher, air pollution might cause several health issues like respiratory problems, lung and skin damage, cancer etc.

Higher demand and rapid growth in use of fossil fuels is another motivation for change. Sustainable mobility can be achieved only by diversifying the propulsion mechanisms since the reserves of oil and coal are finite. Electric vehicles (when ignoring the battery system) require much less servicing in a workshop dependent thanks to much simpler construction, which replaces the combustion and drivetrain components. An EV only has a couple of essential parts like a controller, electric motor and a battery. There is no need for a change of motor oil and other drivetrain fluids, which decreases the number of necessary service visits to a workshop, creating another significant benefit.

The number of EVs in operation is growing and so must the associated infrastructure. In combination with intelligent solutions, operating systems can be developed hand in hand with production of new EVs [25].

The increasing number of charged vehicles means increasing peaks in the power grid that is already being strained due to RES (Renewable Energy Sources) and fluctuating consumption during the day.

Studies have shown that above 90% of the car lifetime is spent in rest, parking [25]. Another fact is that the battery is not being fully exhausted during average daily journey. That gives an interesting opportunity to develop a solution that could help to support operation of the power grid. A car can be for example charged only when the grid has spare capacity. Vehicles can even help the grid with stabilization using its free battery capacity.

Therefore e-mobility is becoming significantly constrained by power grid performance, whose limits must be considered in all subsequent steps of development. Proper infrastructure for EV charging must be therefore implemented.

From a historical point of view, people are used to owning a vehicle. However, is there another way? Since the vehicle is used only for transportation and it is not being used during 100% of its lifetime, it simply does not make sense to own it just for ourselves. That is the reason some companies came with an idea of sharing the vehicles. Future electro mobility might therefore also evolve towards sharing and not owning the vehicle. This approach exceeds the scope of this thesis, therefore it is not evaluated.

5.1 Number of electric vehicles and future development

This section outlines support programmers for electric mobility in selected countries, based on policies known at the time of writing of this thesis.

Norway can be considered a pioneer of e-mobility not only in Europe but all around the world. Since 2017 Norway is the first county where the share of sales of new PHEV (Plug-in Hybrid Electric Vehicles) and BEV (Battery Electric Vehicle) is higher than 50% of total sales including combustion engines. There is substantial support in the form of subsidies, financial reliefs, and provided benefits from the government to the buyers of the EV. EV owners in Norway also do not have to pay highway tax, toll fees and can use the ferry transport and tunnels for free. However the biggest advantage is that buyers can buy the vehicle VAT-free. All these benefits lower the price of EVs compared with ICE (Internal Combustion Engine) vehicles.

France for example has supported "clean mobility" since 2008. From the beginning of 2017 the government provided a grant for buying a new e-vehicle at around 6 000€ + 4 000€ for replacing an ICE vehicle bought before 2006.

The German government approved in May 2016 a grant for buying a new BEV on the level of 4 000€. For HEV (Hybrid Electric Vehicles) the bonus was 3 000€. This kind of support was supposed to be phased out in 2019, however there is some discussion about prolonging this benefit. There is also a 0,5% tax benefit for buying BEV or HEV vehicle since 2019.

In the Czech Republic, owners of EVs do not have to pay highway tax, and in the capital city (Prague) can park also on blue zones that are supposed to be available for parking of residents only. The government also provides grants for companies buying new e-vehicles. Such grants in the optimal case can cover 75% of the e-vehicle investment.

In Austria, different speed limits on high speed roadways might be applied in the future [26].

Multiple forms of motivation to increase popularity of EVs amongst customers is applied, with a goal of increasing the production and use of the e-vehicles.

Annual production of vehicles in Europe is around 19 million units, approximately 20% of global production, mostly with the ICE powertrain. Due to regulations from the European Parliament and Council, cars in production must conform to certain ecological standards. Pollution and greenhouse gases emitted by newly produced passenger cars or light commercial vehicles (vans) are limited by the regulations with evolving targets. The 2015 target is set to 130 grams of CO_2 per kilometer of fleet-wide average emission of new cars. That corresponds to a fuel consumption of around 5.6 liters per 100 km (l/100 km) of petrol or 4.9 l/100 km of diesel. The 2021 target is set to 95g of CO_2/km.

A penalty for exceeding the determined emission levels was applicable for every car produced and registered by the manufacturer [27].

Penalty amounts till year 2018:

- 5€ for first g/km of exceedance,
- 15€ second g/km,
- 25€ third g/km,
- 95€ for each additional g/km.

From 2019 on is the penalty 95€ for each g/km exceeding the target [28].

The best solution for car manufacturers is therefore to produce vehicles which do not emit CO2 to compensate the average emission target. Electric vehicle is considered to be a pollution free vehicle.

Due to these requirements the automotive companies are shifting their production from pure ICE vehicles to HEV, PHEV and BEV.

Multiple long-term forecasts are being published about electric vehicle adoption and how electrification and shared mobility will impact the existing methods of transport. For example, according to an outlook till year 2040 published by BloombergNEF, 57% of all passenger vehicle sales and over 30% of fleet vehicles will be electric.

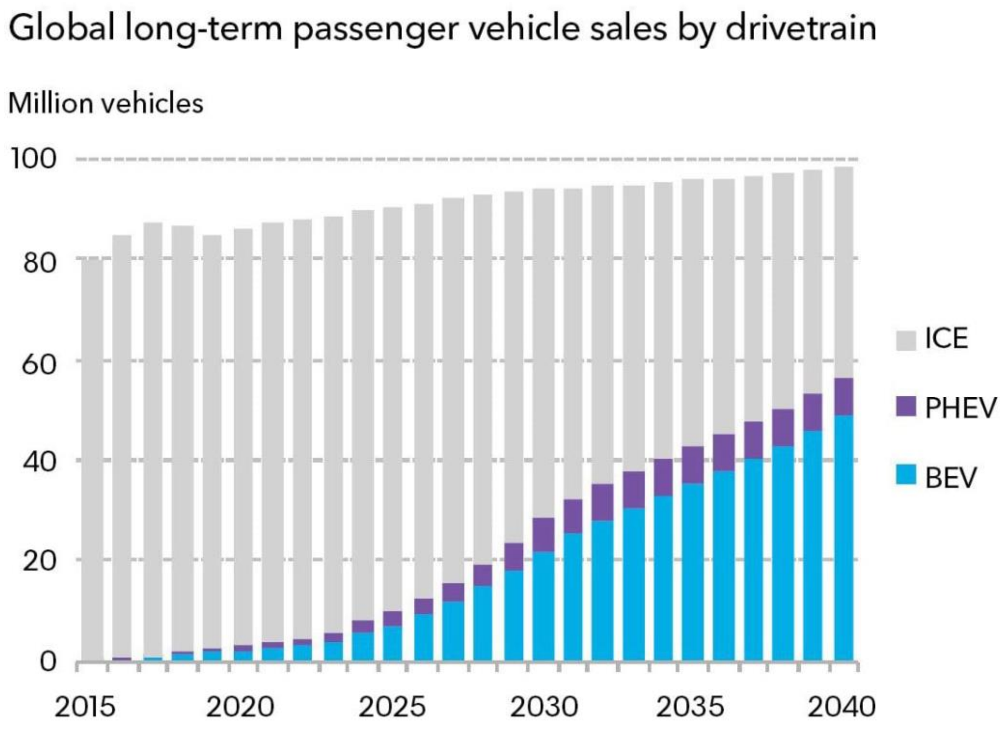

Figure 4. – Electric vehicle outlook 2019 [29]

Such a rapid growth is not only caused by worldwide emission limitations but also by the decreasing price of electric batteries.

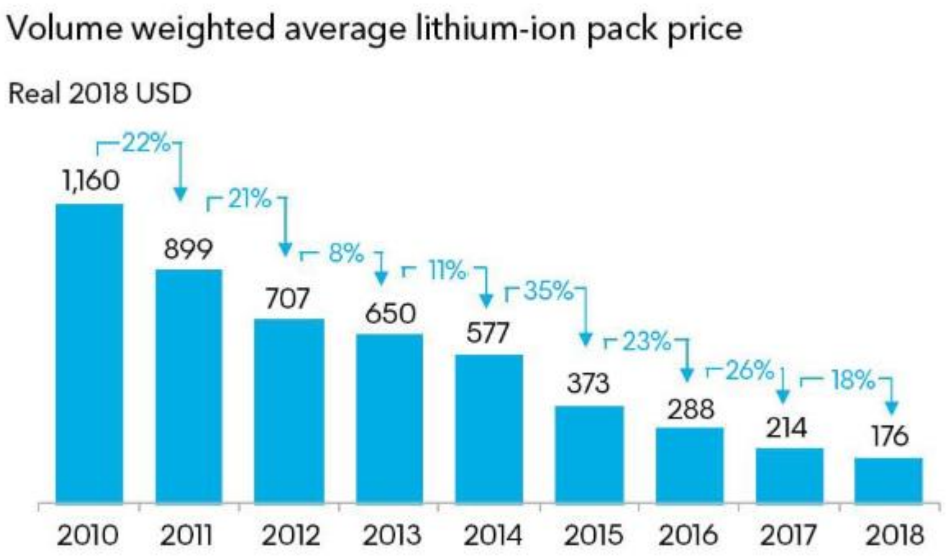

Figure 5. – Price fall of lithium-ion batteries [29]

Share of sales will shift from dominant ICE vehicles to a combination of BEV, PHEV and ICE vehicles.

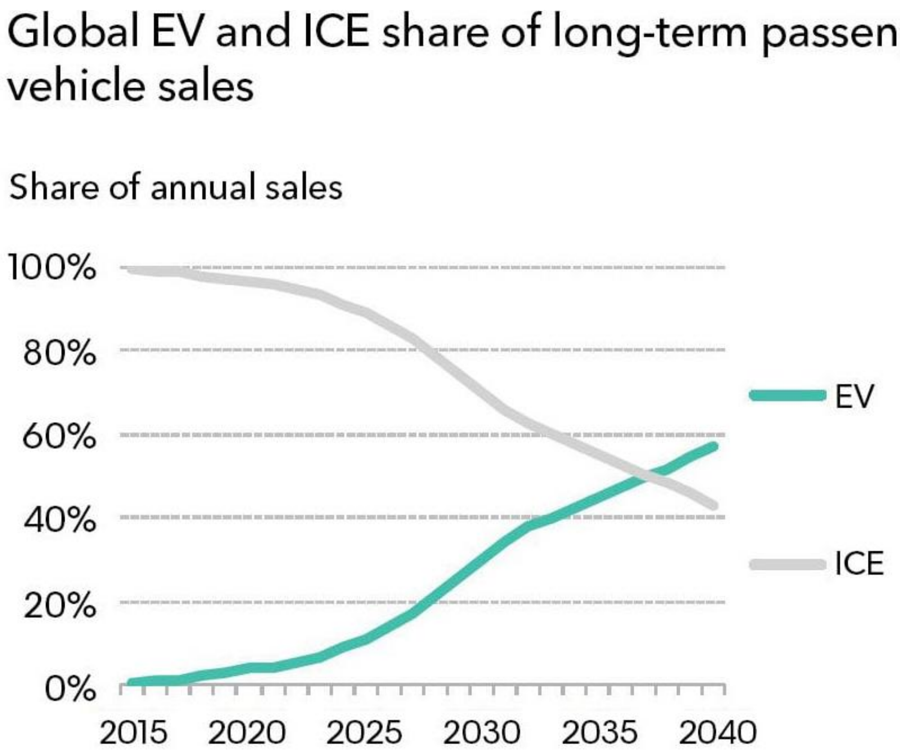

Figure 6. – Share of the different types of vehicles sales [29]

The EV market can be divided geographically into three main segments: China, Europe, rest of the world. China is leading the other markets in EV penetration. It is dominant in all forecasted market segments due to significant policy support on national and regional levels.

However, these scenarios are still hypothetical. The reality is that only customers will ultimately decide the destiny of e-mobility. Drivers are accustomed to the ease of conventional cars so to motivate a customer to switch to EVs, charging must become more available, easier and cheaper. Battery systems will play crucial role in this evolution.

5.2 Blockchain in electro mobility

E-mobility is one of the areas considered most promising for Blockchain applications due to its major features. A simple comparison of the possible domains where the Blockchain is applicable is evaluated in this table:

Domain	Removal of TTP	Digital asset	Multiple parties	Lack of trust	Error prone	Financial settlement	Σ
P2P energy trading	y	y	y	y	y	y	6
Emission allowance	Y	Y	Y	Y	Y	N	5
Grid stabilization	N	Y	Y	Y	Y	Y	5
Energy data exchange	N	Y	Y	Y	Y	N	4
Energy asset register	Y	Y	Y	Y	N	Y	5
EV charging & management	y	y	y	y	y	y	6

Table 2. – Evaluation of Blockchain applications

Two main highly promising use case domains are expected to meet the Blockchain relevance criteria: Peer-to-peer energy trading and EV charging and management. Both these clusters follow current trends in digitalization and facilitate decentralization and electrification via modern digital technologies.

Sustainability topics are increasingly relevant in research communities in the context of all energy related areas. To achieve a decarbonized energy system in Europe, e-mobility is about to play a fundamental role. Especially the charging infrastructure which links the smart power grid system to the mobility. It opens an opportunity to utilize the EVs as flexible units providing demand response supporting flexible power loads or energy storage.

Blockchain is a promising technology that might solve the lack of charging infrastructure by disrupting current business models and for example enabling peer-to-peer sharing of the charging stations, making them publicly available, or supporting the smart grid itself. By implementing intelligent solutions outlined above, final costs of charging might be reduced when rewarding the e-vehicles for their grid services provided.

This technology could therefore partially or completely decentralize the processes connected to the transaction models. Transactions for charging the vehicle could be carried out automatically without any supervision and with partial automation using smart contracts. More detailed applications will be described in the next sections.

Blockchain itself can play a role in every segment of the e-vehicle lifecycle. It can support transparency in the production process, while selling the vehicle to the final customer, while using the vehicle or when the vehicle itself participates in the network (connected via a charger or simply being online for processing and sharing data about its current state, situation on the road etc.). It is indispensable to mention that customer will not need to interact in any way with the Blockchain technology. This infrastructure layer involving the Blockchain technology is acting "behind the scenes" in processing and operating with all kinds of data.

5.3 Sustainability of the upcoming growth of EVs

To achieve sustainability across all industries involved in the e-mobility business, some of the basic measures must be carried out hand in hand in future development.

According to forecasts summarized in the previous chapter, there is a high chance that there will be about 50 million e-vehicles in use worldwide till 2040. But the question is, is or will be the infrastructure ready for so many vehicles that will most probably be charged at the same time during the day?

Will there be a user friendly solution and enough Charging Points to fulfil the needs of the customers? Will the price be adequate and relevant for every customer? There are so many questions that are not answered yet and the purpose of this work is also to point out such future constraints.

Main issues that need to be established and treated more carefully:

- Realization of an adequate transmission and distribution network,
- availability of enough fast Charging Points,
- common solution for easy charging access available to every EV owner,
- lowest price of the charging,
- enough electricity supply in time of peak demand.

There are several ways how to help the current infrastructure to cope with the peak electricity load. Current technology in combination with proper IT infrastructure can provide adequate solution that might help the existing distribution systems.

Most of the entities involved can efficiently apply Blockchain technology to provide the proper solution. In the next paragraphs, some of the future projects and solutions will be described in more detail.

5.3.1 Grid frequency and energy regulation services

A solution called V2G (Vehicle-to-Grid) can inter alia help with the PFC (Primary Frequency Control) in electric networks by utilizing spare battery capacity of the interconnected electric vehicles.

This operation can be performed either by charging or discharging available batteries, or by handling real-time fluctuations while charging the vehicles. A vehicle can participate in the system in two cases. While actively charging the vehicle at a CP or keeping the vehicle simply connected without the need to charge the vehicle battery.

The EV can act as a small energy storage unit that can provide Ancillary Services, helping balancing and providing regulation services within the power grid. This is achieved as a bidirectional power flow between the vehicle and the power grid. When the system frequency decreases the vehicles act as producers and can provide prevention against further frequency drops. Increase of the frequency is simply reduced by absorbing the surplus of the energy into the batteries. Due to the short duration of the provided services (i.e. few seconds-minutes) batteries can be used also during the time vehicles are not being used for its main purpose - transport. This could provide great economic benefits in the form of a reward for the owner of the vehicle, especially in isolated power grids with a significant amount of installed RES.

The EV can participate in the PFC because the signal with information about frequency status is available at any location of the power system at any time. Other Ancillary Services which a vehicle can provide are for example Peak Load Shaving or Net Load shaping.

Vehicles can provide certain level of stability of the power grid and the quality of the power but also earn arbitrage profits from the power-price differences.

When connecting the vehicle to the grid, the owner should have the opportunity to set the desired battery state of charge (SOC) at the end of charging. The charging algorithm should ensure that enough energy is stored in the battery for the next possible trip.

One of the main components in the solution is shown in Figure 7. It is the aggregator which is needed for the participation of the EV in PFC. This aggregator serves as a monitoring component of the fleet of vehicles connected to the power grid. It creates a virtual power plant whose performance is derived from the number of connected vehicles and their available battery capacity. Such a power plant receives signals from the TSO (Transmission System Operator) and forwards them to selected vehicles with specific commands. Based on the grid requirements the vehicles respond.

The aggregator should also play the role of a market coordination party, estimating the regulation capacity of all connected elements and choosing the optimal bidding strategy. When the market clearing is finished, participation of the vehicles is specified and vehicles should act based on grid requirements.

Another component in the system is the V2G controller which should monitor and make decisions based on real-time frequency and detailed battery status. The controller should therefore decide whether to charge or discharge a battery system in order to suppress frequency fluctuations [30].

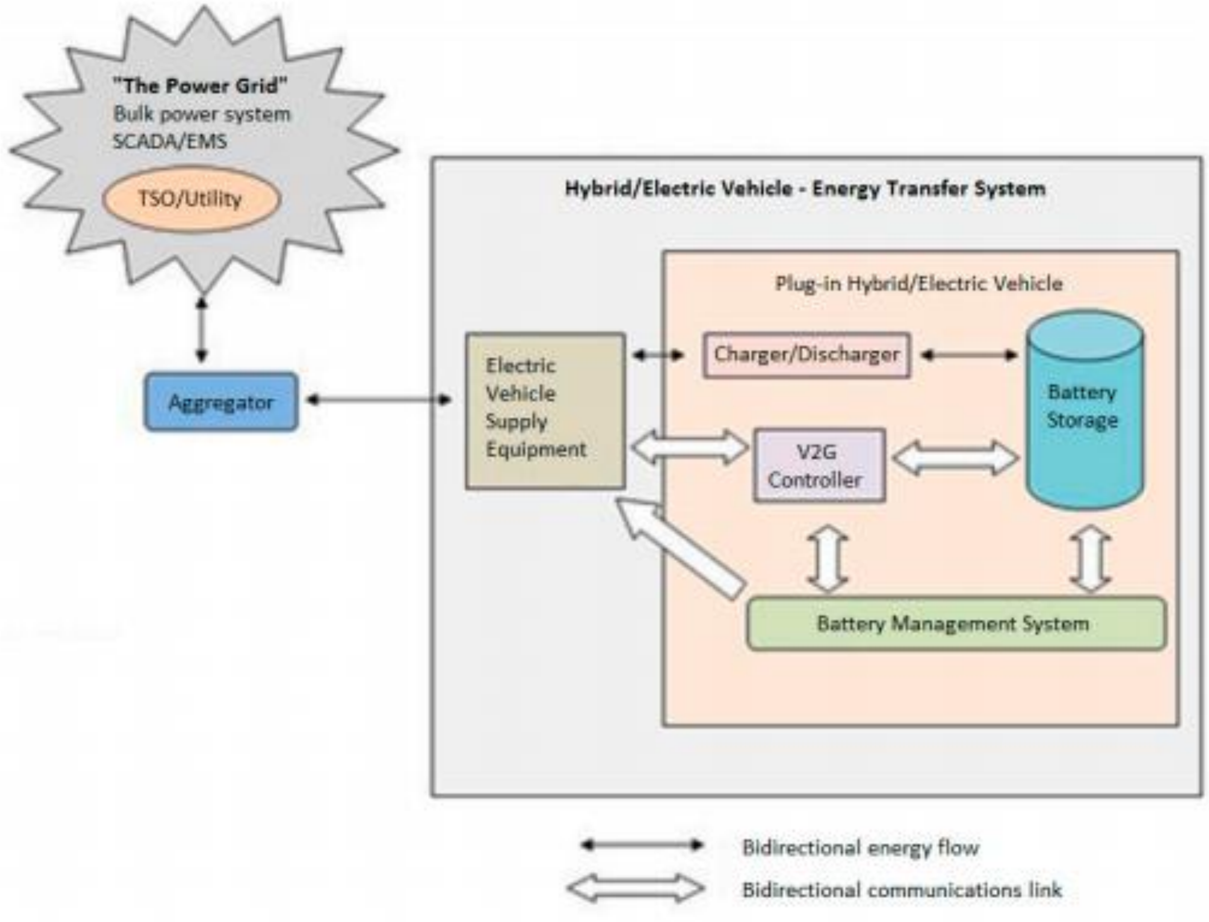

Figure 7. – Schema of the Vehicle to Grid (V2G) operation participating in Primary Frequency Control [30]

Battery Management System monitors the state and health of the battery and provides interface between the vehicle and battery itself. Based on this system, deeper logic can be implemented using parameters such as time of charging, length of the next trip etc. to define the maximum possible discharge level of the vehicle battery.

This solution can improve the actual performance of the current electricity infrastructure without necessity to install new conventional power generating units, other types of battery storage or other types of reserves.

In the best case, owners of the EVs who plug their vehicle into the grid even though no battery charge is need, can be paid just for providing its battery equipment and spare capacity. A minimum number of electric vehicles and sufficient charging points is mandatory to have a fully working solution [30].

5.3.2 Vehicle-to-Home

This use case is where EV batteries participate as a residential battery storage and backup power supply during grid outages or when more electricity is drawn than local sources (such as photovoltaic panels) can supply. Connecting the vehicle to a multifunctional charger also gives the owner a possibility to disconnect from the grid completely. V2H (Vehicle-to-Home) approach therefore avoids the infrastructure and tariff problems inherent to V2G. V2H is more limited because only one vehicle is typically connected to a single house. Involvement of transmission and distribution is minimal compared to networks with centralized generation, so costs of transmission infrastructure and transmission losses are highly reduced.

The trade-off is in simplicity versus flexibility: more vehicles that work together can offer larger and more flexible battery storage but with more difficulty in controlling them.

This system is generally considered an emergency solution mostly covering the case of a grid power failure which cannot be easily predicted. Owning an installation of photo-voltaic panels provides another opportunity to use surplus of the energy produced to store it “for free” in the car battery system. In most cases, the household will be equipped with a battery system that fulfills its original purpose to store the energy for the rest of the day when the sun is not shining. The exact mode of operation depends on the household battery capacity which can be enhanced by adding also the vehicle battery capacity. Home battery system is a much more mature technology because it is only used to store and provide electricity covering the household needs. The vehicle battery is designed to power the engine so the case of providing capacity to the household might have negative effect on the lifetime of the battery (detailed battery degradation model is shown later in this thesis) [16].

If peak power consumption becomes managed by each household by offsetting the consumption of high power appliances using the vehicle battery, some of the power stations that are reserved for times of peak demand will not have to be started or at least can used less often. In this case the CO2 production would be reduced. However further research is required to analyze and define the costs reduction and possible benefits in V2H integration.

V2H and V2G can work as a combined solution which might provide a spectrum of benefits when proper infrastructure and adequate hardware is used.

6. Determination of price for charging

The main purpose of this thesis is to specify a formula for price of charging and to show how could be the price of charging evaluated according to various actions of an e-vehicle which can act as an active node in the grid. There are multiple solution described that can be compared with each other using basic economic indicators. Some of the visionary projects and technologies will be explored in these calculations to indicate what benefits they could bring.

In order to develop such a formula, all necessary input data like technical parameters of the EV and charger hardware, personal driving data, prices, fees, fixed and variable costs must be established.

Pricing of the hardware of the CPs can be obtained easily. More difficult task is in obtaining pricing data of the new technologies and traditional IT as well as Blockchain-based solutions, quantifying negative effects of the bi-directional charging and discharging of the battery, evaluating data about driving styles and driver preferences etc.

So far there are not many commercial projects which have already implemented such technologies or the IT infrastructure which would be based on Blockchain. Since all these applications are in early stage of development, it causes the prices to be higher compared to using classical IT infrastructure with no extra features involved.

Setting the price of the domestic charging is mostly determined by the household electricity provider with which the owner has signed a contract. This formula and calculations are being evaluated only for comparison reasons.

The level of charging price mentioned in this thesis can be lowered by a certain amount of extra revenues, which the e-vehicle might be rewarded when providing grid AnS. The amount of the V2G Revenue is calculated to be minimal and the approach still remains profitable, compared to classical, non-V2G solution of charging.

Every vehicle owner uses the vehicle for a different purpose. Preconditions and assumptions for case of home charging are then:

- Usage of the vehicle involves only daily work trips,
- such vehicle has a total mileage approximately 20 000km per year,
- price of electricity, maintenance, grid connection is stable within project lifecycle,
- number of charging cycles is based on the number of workdays during the year,
- charging session is not interrupted,
- charging and discharging of bi-directional energy flow has the same efficiency,
- charger operates with adequate performance.

When all assumptions are defined, calculations and formulas can be specified.

6.1 Home charging

To develop a formula defining the price of charging, all necessary parameters that are relevant must be clarified and described first. These inputs can be divided into four major groups. The first group describes all data common to all formulas. This section therefore contains the description of the electric vehicle configuration, needs of the driver, charger parameters and electricity and financial data.

In the second section, all specific data mandatory for traditional charging are specified. These data include for example basic IT system costs and integration costs for value-added services.

The third part describes all specific data related to Blockchain based management like development of Blockchain infrastructure and Blockchain operation costs.

The last part includes the rest of parameters or costs that are not directly influencing charging itself however can be considered as extra services also provided by a Blockchain solution.

6.1.1 General inputs influencing all methods of charging

Physical parameters of the vehicle:

- Battery capacity (kWh)

Battery capacity is a technical parameter representing the amount of energy that can be extracted from the battery in certain conditions. This capacity serves as energy storage and is used to power the propulsion system. In vehicles, this capacity is represented by kilowatt hours. Based on the battery capacity, the average driving distance can be calculated using vehicle “consumption”.

In modern BEVs, the battery capacity level is typically 35-100kWh. For example a model of Volkswagen e-golf has capacity 35,8kWh, Nissan Leaf 40kWh, BMW i3 42,2kWh, Audi e-tron 95kWh, and Tesla X 100kWh [32].

- Consumption (kWh/100 km)

The average vehicle “consumption” and battery capacity determine the estimated driving distance per charge. This parameter in EV terminology defines how much of the battery capacity is needed for a car to travel 100 kilometers (or miles). It is difficult to calculate the exact consumption of an electric car due to many external factors playing a major role in influencing this parameter. Consumption can be affected for example by the driving style or the use of car heating / air conditioning.

- Peak charging capacity (kW)

When charging a battery, a charger with specific configuration must be used. Not every battery can be connected to any charger. Depending on the performance of the battery and the internal vehicle system, there is maximum power input which the battery can handle and not get overheated or damaged. This maximum energy input is called peak charging capacity.

- V2G discharging capacity (kW)

In case of a V2G solution, the EV is connected to the grid and can provide several services to the grid. In such case, energy is drawn from the vehicle and its maximum instant output is peak discharging capacity which is measured in kilowatts.

- Optimal charge-discharge interval (%)

When the EV is connected to the public charging station, the user will most probably be limited by the time that he wants to spend waiting for the charging to complete. Most likely the user will not charge the vehicle from a completely discharged state (due to the limited accessibility of the existing charging infrastructure and the resulting range anxiety). Therefore the interval describes the expected change in percentage of battery capacity from the start of charging till departure from the CP. In a DCFC system, optimal and the fastest charging is from 20 to 80% of the battery capacity. Therefore 80% is the expected percentage capacity of battery after leaving the CP and 20% is the initial battery state before the start of charging [24].

- Battery intake

A car battery is limited by the power it is able to absorb while charging a vehicle. Therefore in some cases, the driver cannot use a DCFC charger due to these battery limitations. This parameter is influenced also by the average charging efficiency which is estimated to be about 90%. This means that a charger with output of 7,4 kW can power the battery with a lower efficiency of 6,66 kW.

- Cost of battery degradation for a grid service event

After providing some types of Ancillary Services, battery capacity gets permanently lowered due to internal degradation. This effect can be quantified using inputs such as severity of the event, battery cost, and residual value of a battery at the end of deployment in a vehicle (followed for instance in secondary use as stationary energy storage).

- Charging price

Amount of money that owner of the electric vehicle has to pay to charge his vehicle, based on current battery SOC (State of Charge).

Needs of the driver

- Annual/daily mileage (km)

Every owner uses the vehicle for a different purpose and with different frequency. However most of the existence of the vehicle it is parked. This parameter therefore describes how much is the vehicle being used for example on daily basis, where the owner drives his car to work and then back home. Information about the daily mileage might be crucial for calculating V2G / V2H benefits.

- Comfort with the discharge level (SOC_E)

When an owner of the EV decides to connect his vehicle to the grid to charge the EV and also provide supporting services like grid balancing, he will likely want to select the battery % level with which he is happy in case he needs his car to be ready for a future trip. Observation of this limit constrains the operating processes in V2G / V2H services.

Every connected vehicle must provide its information about SOC_0 (initial State of Charge) of its battery when being connected to the charger. The EV owner (or an automated algorithm acting on his behalf) decides what is the minimum SOC_E to make sure the user is satisfied and ready for his next trip.

$$SOC_0 = SOC_E - Driving\ distance \times AVG\ consumption$$

- Length of the charging session

This parameter contributes to all charging price formula calculations. According to the time spent at specific CPs (home stay overnight, between morning and evening commute, lunch break, shopping break, highway stop), predictive calculations can be made. For instance, most of the vehicles are being parked during the night which provides an opportunity to predict and work with such data.

- Roaming needs

Roaming in case of e-vehicle charging refers to driver's ability to charge his vehicle at various CPs even if they are only a customer of one service provider. In practice that means that only one customer account is needed. To achieve such situation, like in telco industry, providers must cooperate together and agree on several conditions which provide benefits to all parties involved – the customer and both providers.

- End of life Battery threshold (EoLBT)

Battery capacity is being decreased by usage and aging. When using the battery in a V2G mode, degradation can be accelerated by providing AnS. The owner of the vehicle then must decide, what is the limit of acceptable battery capacity, before the vehicle battery is replaced. Mostly, this value is around 30%, meaning the final battery capacity is 70% of the initial state when the vehicle was new. This parameter plays a crucial role in our calculations.

- Number of V2G hours spent

This value defines how long is the e-vehicle connected via the charger to the grid and provides any AnS. Based on that the EV is rewarded a certain amount of money which decreases the final price of charging.

Electricity sector parameters

- Cost of grid connection (EUR/kW – monthly or annual)

To have the possibility to connect and charge the electric vehicle, the EV owner has to pay fees for the grid connection which is suitable for such purpose. This value can differentiate in case of a bi-directional energy flow (V2G mode). This value might be fixed by a contract during the initial process of grid connection and then paid monthly/annually.

- Cost of commodity (EUR/kWh)

In our case the electricity cost is based on the residential tariff derived from the price list of the retailer. Such tariffs can have different prices at different hours (in time of peaks the electricity prices are higher, in times of energy surpluses prices can be negative, meaning the customer is being paid for using extra electricity for example in their in-car battery). This value in our case is fixed during the time and project lifetime to simplify the calculations. It is expected that the grid connection point is equipped with a smart meter.

Financials

- Discount rate

Discount rate is used to determine the present value of the future cash flow. In V2G projects, this value fluctuates between 6 – 10% [33], [34]. In our thesis is therefore used discount rate 8%.

- Number of years

Project years in which is the vehicle considered sufficient to fulfill all driving needs of a customer. This parameter highly correlates with battery degradation and EoLBT. The number is derived from the final battery state.

- Annuity

Series of equal payments with equal frequency.

- V2G Revenue

This Revenue is the amount of money received by the EV owner after providing AnS with the vehicle. This revenue is calculated using multiple models described in this thesis.

Other parameters

- Internet connection cost,
- repairs and maintenance cost,
- battery cost.

6.2 Charging formula

6.2.1 Home charging with no additional features

The home charging price formula and price definition in this thesis serves for comparison with the V2G approach and extensions including the Blockchain technology which might in certain conditions provide benefits beyond economic ones. Currently the price of charging is set up by the retail electricity provider, typically a stable value based on generic electricity rates offered by the supplier company. This cost is mostly directly influenced by the current cost or the selected electricity tariff.

The scope of this thesis indicates that some input assumptions need to be simplified. Certain calculations are therefore used only for illustration purposes. The data used should however reflect a real-life use case and should be based on verified and trustworthy sources.

First part of the calculation describes all fixed costs, which are assumed to be passive during the project lifetime. A major part of fixed costs is the electric vehicle which plays dominant role in comparing financial benefits, with the EV charger being also a complex and expensive device. Given the complexity of these major assets it is prudent to expect certain amount of maintenance costs during the project lifecycle.

Second major part is the cost of grid connection which consists of the fee for initial connection and periodic fees during the project lifetime. For the current section this parameter is considered to be a fixed value.

$$Fixed\ costs = EV + Grid\ connection + Charger + Maintenance$$

To develop a realistic computation a prediction of total annual mileage must be defined. Average consumption of a specific vehicle can be easily measured, therefore this value is certain. For example, a model of Nissan LEAF has average consumption of 16 kWh/100km [22]. This value is used as a basis in calculations.

$$Annual\ consumption = Total\ mileage \times AVG\ consumption$$

Knowing a charging efficiency (value described in an earlier paragraph) the total cost of charging per year can be easily calculated while knowing the supplier tariff price and therefore the electricity price.

$$Annual\ charging\ cost = \left(\frac{Annual\ consumption}{Charging\ efficiency}\right) \times Eletricity\ price$$

$$Total\ costs\ per\ EV\ lifecycle = \sum Annual\ charging\ cost\ + \sum Fixed\ costs$$

Total cost per project lifetime can be achieved by summing the annual cost over the project lifetime and adding total fixed costs over project duration.

The charging cost shows how expensive is it to charge the vehicle when the user connects the EV with certain SOC_0 to a charger. This is the cost calculated for one charging cycle which differs every time according to the length of the driver´s previous trip and the current battery capacity level.

$$Number\ of\ kWh = (SOC_0 - SOC_E) \times Battery\ capacity$$

$$Charging\ cost = Number\ of\ kWh\ \times Electricity\ price$$

Some parameters can play both major and minor role in the formula. The formula presented here is simplified to provide a basic overview of the process how the price can be calculated. All other listed parameters bellow take also part in defining the final price of the charging.

- Peak charging capacity per charger (kW),
- battery capacity,
- profit.

In this “home vehicle charging approach” the vehicle spends most of its lifetime parked at home. Battery storage is therefore used only for one simple purpose – to provide the source of energy to propel the vehicle. This indicates that such usage is not economically beneficial compared to using the battery of the parked vehicle for other purposes described in the next paragraph.

6.2.2 Home charging with V2G mode

Setting up the V2G approach of charging can provide multiple benefits if enough cars are connected and the solution is well prepared. EV owners and GSO (Grid System Operators) could exchange benefits in the form of lower operational costs, savings from deferred investments, or extra AnS revenues (V2G revenues).

EVs can act as an energy storage and can support the grid as demand response or frequency regulation. When correctly implemented, this approach can also provide Load Management for RES integration and to reduce or defer future investments in building additional electricity infrastructure needed due to increasing penetration of the RES.

Both stakeholders (GSO and EV owners) have different motivations for realizing the V2G charging approach. GSO´s primary motivation is to avoid potential operational risk of disbalance in the grid. The more EV is sold the bigger is the risk due to uncontrolled charging heavily affecting the operation of the grid. Operating costs could therefore easily increase. To prevent that, transformation from “passive” to “active” grid is the key where EVs shift from being an issue to being a part of the solution which helps the grid to operate properly. In such scenario, costs of a GSO could decrease and resilience of the grid would get enhanced.

The motivation of the EV owners is of course to decrease their charging costs or to get additional revenue. However, owners must choose to provide V2G services knowing the negative implications of V2G side effects like the decrease of the driving limit and degradation of the EV batteries.

Figure 8. shows that when the quantity of the EVs is small, impacts of the EV charging benefits and issues can be negligible. With diffusion of EVs the GSO needs to upgrade the grid, grid facilities, and build adequate charging infrastructure. GSO or the electricity retailer (in unbundled electricity systems) choose the proper charging price strategy to achieve adequate amount of revenue. As the number of the EVs raises, the grid should become smarter although more sophisticated energy management.

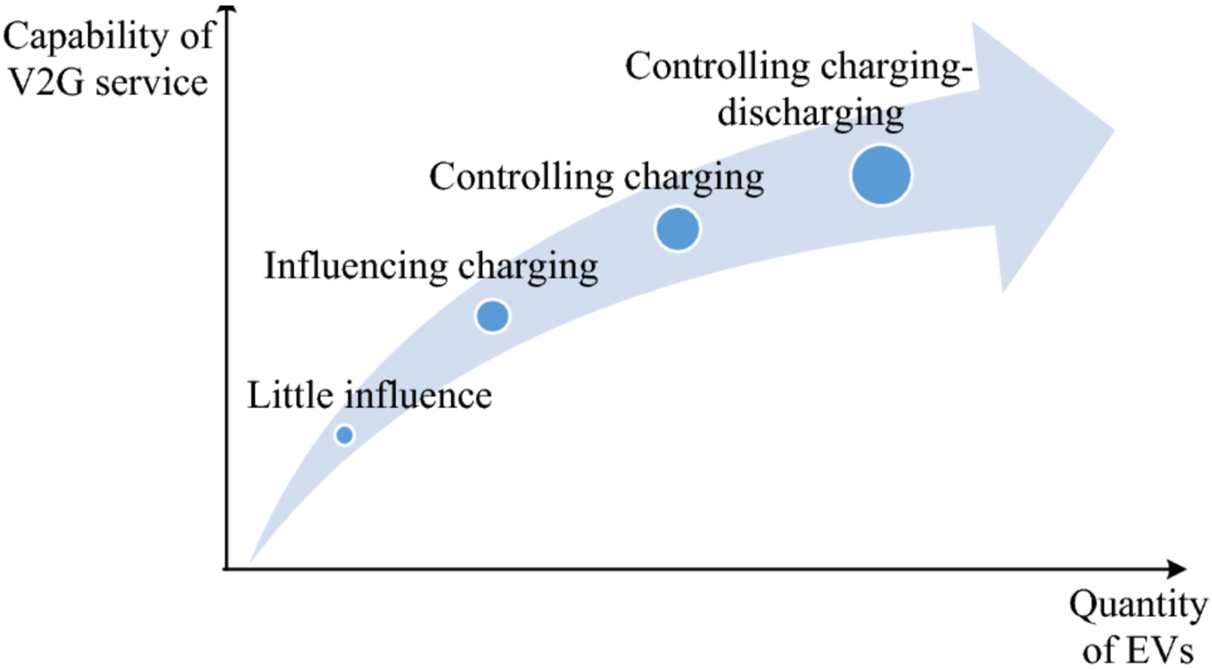

Figure 8. – Coevolution of V2G services and the grid [35]

Given the scope of this thesis, only the case of V2G Peak Load Shaving is described and evaluated to show possible benefits while no extra investments need to be committed from the GSO side.

Blockchain in this solution can contribute in the form of a transaction layer which might be utilized multiple times per charging session. Details of each transaction are then verified and recorded in the transaction ledger. Immutable, notarized record of actions of the involved parties stored on Blockchain can help to reduce costs to the electricity providers and gives a clear overview of the vehicle behavior in the grid itself. Each vehicle can have a unique ID assigned with which it will be recognized in every established connection event.

While the car is connected and supporting the grid, its SOC is changing according to requirements of the grid. To accommodate the driver´s stochastic future driving need, only the residual battery capacity level can be available online to provide V2G services.

In this case, the revenue based on providing AnS can be specified in multiple ways. This revenue must be proficient for the GSO, basically the lowest price that still motivates the EV owners to provide their car and use the EV for bi-directional charging.

In this case, the fixed costs are being calculated the same way as is in the previous section.

$$Fixed\ costs = EV + Grid\ connection + Charger + Maintanance$$

V2G revenue is the most sophisticated parameter in specifying the charging price. This value can be formed in multiple ways, however given the scope of this thesis the establishment of this variable will be simplified. One of the options to set up this value is to calculate the cost of battery degradation for a grid service event or simply to choose a certain amount of money and select revenue based on the time spent on the grid providing AnS service. Total demand need and prediction of the grid regulation needs cannot be simply predicted and that is the reason it is simplified in this thesis.

$$V2G\ revenue = Time\ spent\ supporting\ grid\ \times Revenue\ per\ hour$$

or

$$V2G\ cost = Cost\ of\ battery\ degradation\ for\ a\ grid\ service\ event + Profit$$

Annual price of charging is again based on the total vehicle power consumption multiplied by the electricity price, with additional cost of extra power provided whilst providing AnS (power consumed multiplied by price of electricity). Total costs of charging the vehicle are then based on total consumption plus fixed costs minus sum of raised revenues during the year. This formula shows where the benefit of the V2G solution takes a part.

$$Annual\ charging\ cost = \left(\frac{Annual\ consumption}{Charging\ efficiency}\right) \times Eletricity\ price + Cost\ of\ V2G\ provided$$

$$Total\ costs\ per\ EV\ lifecycle = \sum Annual\ charging\ price\ + Fixed\ costs - \sum \text{V2G revenue}$$

$$Charging\ cost = Number\ of\ kWh\ \times Price\ of\ kWh - V2G\ revenue$$

This is the main purpose of the V2G mode application which creates a benefit for the EV owner by reducing total costs derived from the electricity bills. Based on the size of revenue, cost is successfully reduced. Detailed comparison of the two approaches is described in the next paragraph.

Extra parameters which could also play a role in formula definition are:

- End of life battery threshold,
- time spent providing AnS,
- battery replacement cost,
- battery degradation,
- residual value of the battery for secondary use (e.g. as stationary energy storage),
- V2G Revenue.

6.3 V2G revenue

V2G Revenue is based on services which are provided from the EV battery system. The number of electric vehicles increases and therefore the degree of their integration in the power grid utilization must increase as well to have a chance to participate in grid Ancillary Services. However, the capacity of a single vehicle is not enough to meaningfully contribute to these grid Ancillary Services. Thus, a larger number of EVs must cooperate simultaneously to provide the needed support. The most promising Ancillary Services which can be provided by such a pool are Peak Load Shaving, Net Load Shaping or Frequency Regulation.

6.3.1. Peak Load Shaving

Having multiple EVs connected together in the grid which are ready to provide its services offers a major opportunity for a GSO to balance the grid during peak load spikes. Shaving such spikes can strengthen the stability of the power systems, alleviate supply shortages and defer increases in grid capacity. This concept enables a reduction in the cost of transmission infrastructure.

When the peak load occurs, a fleet of connected EVs can act as a quick-responsive resource. EVs then feed the grid with the stored energy. The most common scenario covers also Smart Charging where vehicles will shift their charging session to a later interval, because as can be seen from the daily diagram of residential area in Figure 9., most of the peak load spikes are likely to occur when customers arrive home from work (17:00-21:00) and start charging their EV immediately [36].

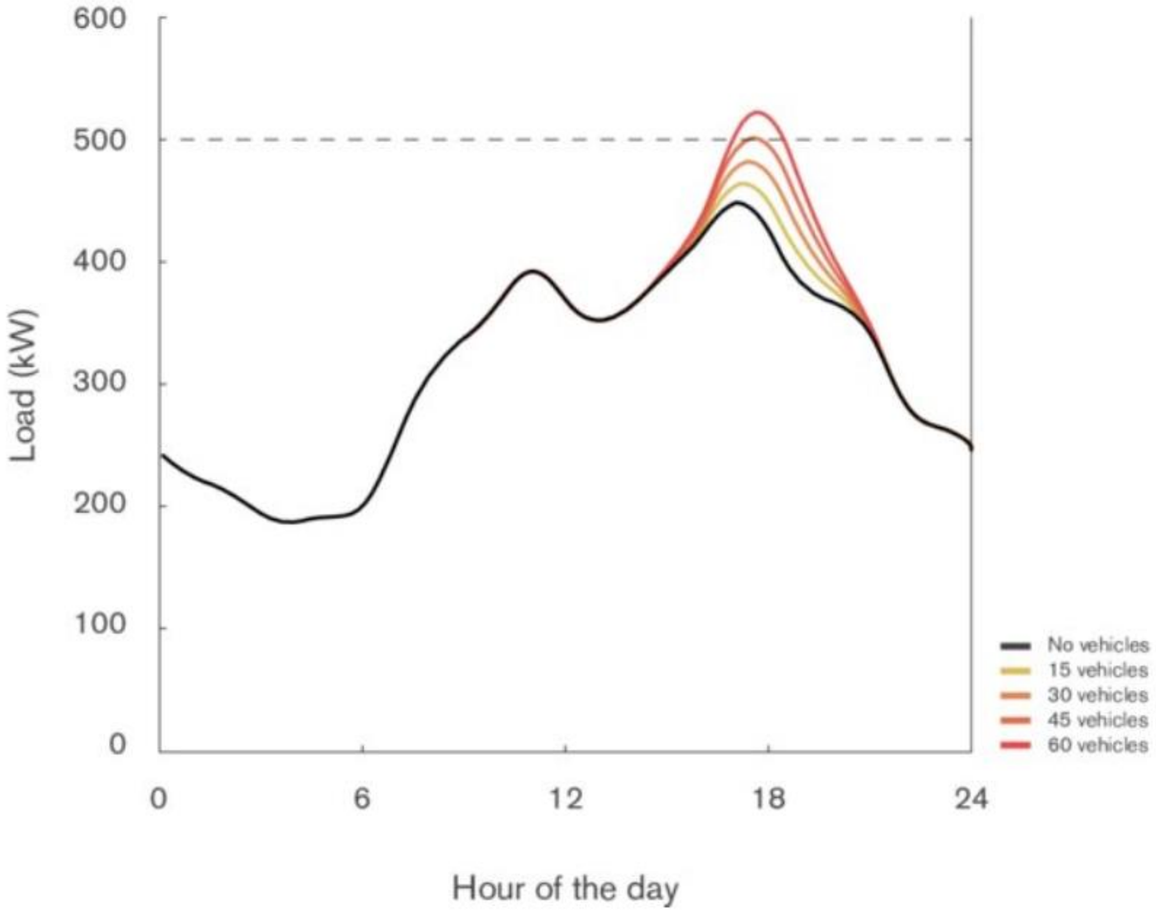

Figure 9. – Daily diagram of electricity consumption in a residential area increased by raising the number of connected EVs with a 2kW charger [36]

The publication "Quantifying electric vehicle battery degradation from driving vs. vehicle-to-grid Services" [37], describes two approaches to reduce the peak loads (caused not only by electric vehicles).

The first one describes only a postponing of the charging session during the peak load times and its effect on the battery degradation in a 10-year interval (this approach should not damage the battery since the battery is not used in this case for bi-directional energy flow). The second one takes into account providing AnS and its estimation is established for three different places (which might simulate different climate conditions), using 100 vehicles and shows the degradation of a battery by aging and cycling (connected every day to the charger).

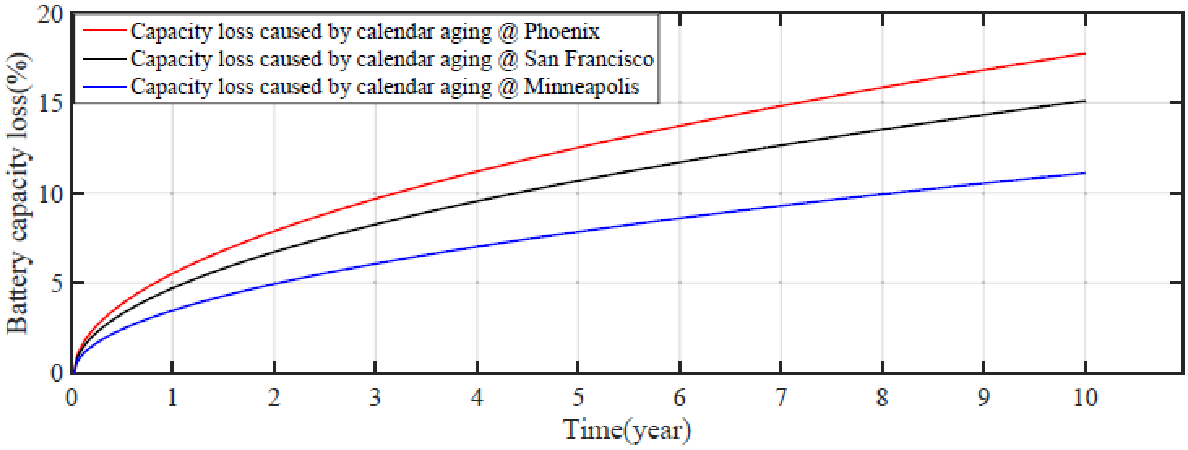

Figure 10. – Battery degradation caused by aging [37]

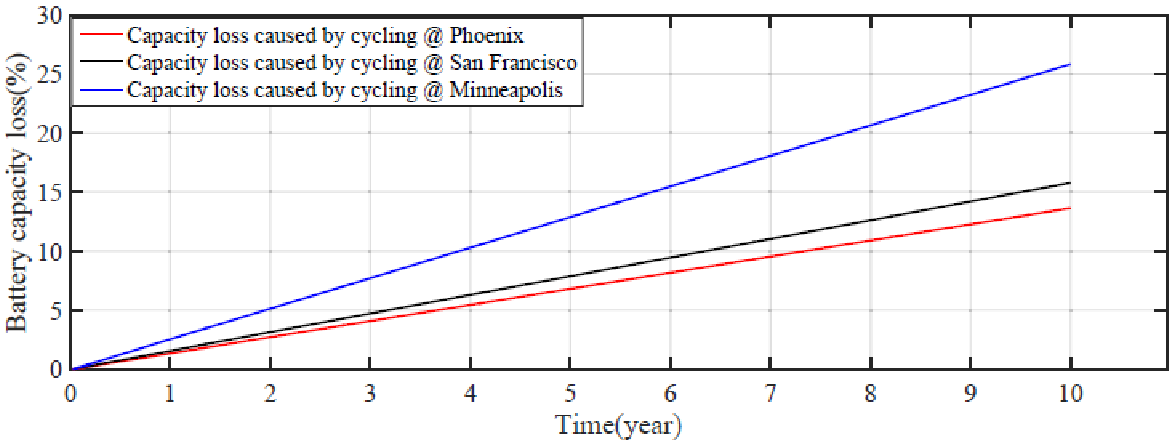

Figure 11. – Battery degradation caused by 2-hour cycling every day [37]

The calendar battery loss is faster at the beginning and the lower temperatures are helpful to reduce the speed of battery degradation. The number of peak shaving hours affects average capacity as shown in Figure 12.

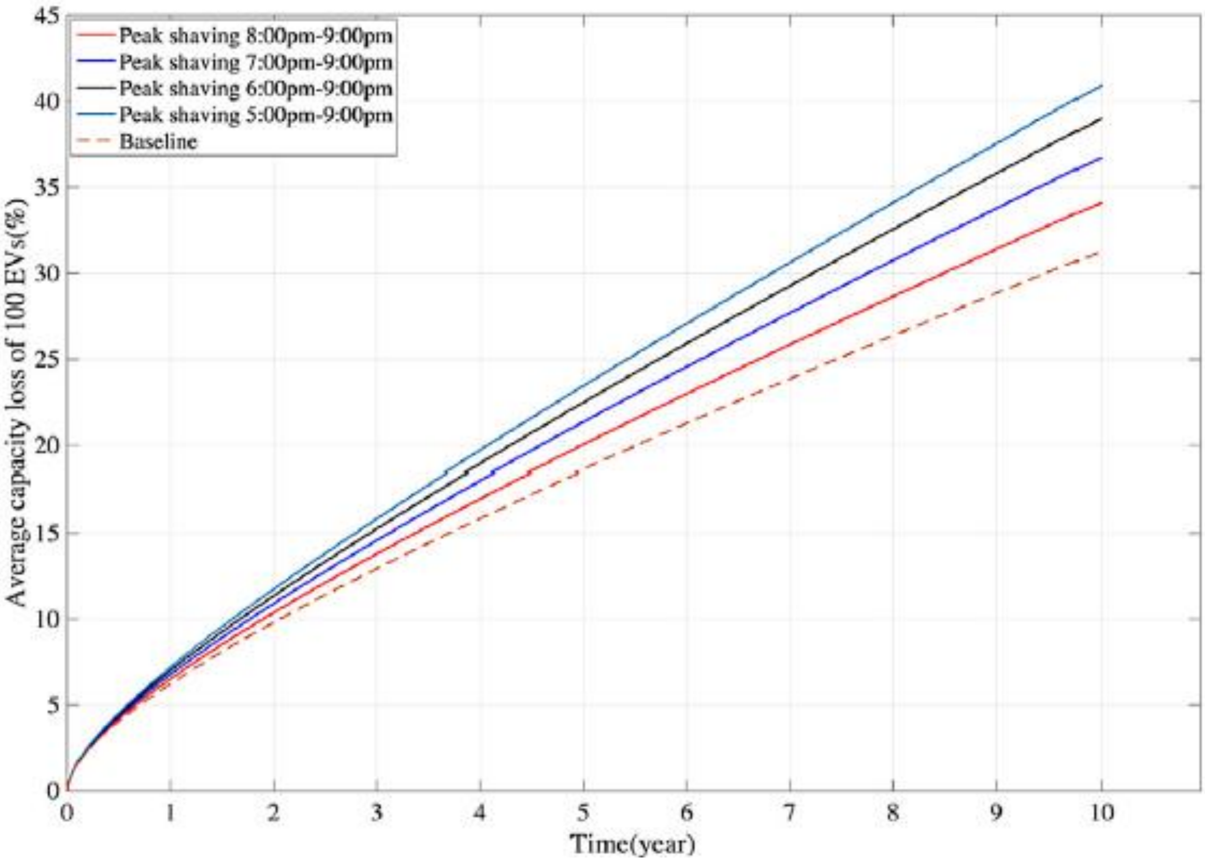

Figure 12. – Average 10 year battery degradation of 100 EVs providing Peak Load Shaving at different hours [37]

It should be noted that average battery degradation is based on Peak Load Shaving provided every day for 10 years of activity. In real life this might not be the relevant case but it offers a very good overview of the negative effect of cycling with battery aging to the DOD (Depth of Discharge) of the battery itself.

Data points for the total loss of the capacity during 10 years of performing grid services, derived from Figure 12:

0 hours shaving = 31% (no grid service provided)

1 hour Peak Load Shaving = 34,2%

2 hours Peak Load Shaving = 37%

3 hours Peak Load Shaving = 38,8%

4 hours Peak Load Shaving = 41,1%

Battery degradation caused only by aging and normal usage of the EV in ten years is established to be about 31% [37]. The revenue can be therefore calculated from the data above.

6.3.1.1. Revenue based on cost of battery degradation

To calculate the revenue based on the cost of battery degradation for a grid service event, a formula qualifying all the data must be used [37].

$$C_{BD} = \frac{Q_{loss}\%}{\eta_{\%}} \cdot B_C$$

C_{BD} ... $Cost\ of\ battery\ degradation\ for\ a\ grid\ service\ event$

$Q_{loss}\%$ ... $Capacity\ loss\ in\ a\ grid\ service\ event$

$\eta_{\%}$ ... $end\ of\ life\ battery\ treshold$

B_C ... $Battery\ replacement\ cost$

Knowing the price of battery degradation cost for a grid service event, the V2G revenue must be higher than this value.

$$V2G\ Event\ revenue > C_{BD}$$

This revenue depends on the AnS which is currently provided, since every AnS has a different effect on battery degradation. To get a basic overview of the subsequent process of calculation, further steps concerning specific services must be described.

Loss of battery capacity in a grid service event can be calculated for every scenario based on the number of hours performing the grid service of peak shaving. This value is calculated based on extra degradation caused by the amount of hours spent Peak Load Shaving.

$$Q_{loss}\% = \frac{DOD_B - DOD_x}{3650}$$

DOD_B ... $Depth\ of\ Discharge\ after$ 10 $years\ of\ no\ grid\ service\ support$

DOD_x ... $Depth\ of\ discharge\ after\ ten\ years\ of\ grid\ service\ support\ per\ x\ hours\ daily$

When the capacity loss in a grid service event is known, the cost of battery degradation C_{BDx} can be calculated from the formulas in this section for x = 1, 2, 3, or 4. This value is calculated with battery replacement price 5400€ [37], which determines the final value of C_{BD}.

$\eta\%$	5	10	15	20	25	30	35	40
C_{BD1}	0,0095	0,0047	0,0032	0,0024	0,0019	0,0016	0,0014	0,0012
C_{BD2}	0,0178	0,0089	0,0059	0,0044	0,0036	0,0030	0,0025	0,0022
C_{BD3}	0,0231	0,0115	0,0077	0,0058	0,0046	0,0038	0,0033	0,0029
C_{BD4}	0,0299	0,0149	0,0100	0,0075	0,0060	0,0050	0,0043	0,0037

Table 3. – Cost of battery degradation for a grid service event based on End of Life Battery Threshold

These results provide the value of the V2G Revenue (in euros) which should be equal or higher (to account for the profit) for every single grid service event. This calculation can be therefore a baseline for establishing compensation policies, serving to make EV owners aware of the monetary cost in case their vehicle is used for such grid support.

It is also very important to mention that this calculation covers only the cost of battery degradation for a grid service event, i.e. how expensive is the event provision regarding the battery life. This approach provides a valuable overview and transparent formula definition. However, a better case with more relevance for customers is described in the next section.

6.3.1.2 Revenue based on threshold setup

Another approach is to set up the threshold with which is the vehicle owner happy. This case is more relevant due to the capacity of the battery and user comfort.

When we consider the battery capacity of Nissan LEAF to be 40kWh (new vehicle) and the energy consumption around 16 kWh/100km, the total driving distance is about 250km per fully charged battery.

When we consider battery degradation, this mileage decreases rapidly during the years and due to the AnS provisioning.

End of Life Battery Threshold	20%	25%	30%	35%	40%	unit
Remaining battery capacity	32	30	28	26	24	[kWh]
Total mileage	200	187,5	175	162,5	150	[km]

Table 4. – Remaining capacity based on EoLBT

When the end of life battery threshold EoLBT is set by the owner to be 20%, the car can operate 5,5 years when no Peak Load Shaving is provided and 5 years when the grid service is provided 1h every day. Table 5. shows how long a vehicle can operate till the designated end of life battery threshold is reached.

End of Life Battery Threshold	20%	25%	30%	35%	40%
Peak Load Shaving 0h	5,5	7,4	9,5	11,5	13,5
Peak Load Shaving 1h	5	6,7	8,5	10,4	12
Peak Load Shaving 2h	4,7	6,1	7,8	9,4	11,2
Peak Load Shaving 3h	4,3	5,8	7,2	8,8	10,4
Peak Load Shaving 4h	4	5,4	6,9	8,3	9,8

Table 5. – Number of active years of the EV based on the EoLBT definition

According to this table a driver can use the vehicle for regular purposes and peak shaving for 9,8 years if he decides that the End of Life Battery Threshold for him is 40% (150 km driving distance per fully charged battery).

In this use case, two options are compared with specific EoLBT. The first case considers 20 % of EoLBT and is comparing Home charging when no V2G service is provided, and 1hour Peak

Load Shaving daily. As can be seen from the table above, durations of chosen options are to be 5,5 and 5 years.

The second example is calculated with 40% of EoLBT and compares home charging with no V2G service and 1 and 3 hours of Peak Load Shaving provided daily. For these three options the lifetime is 13,5; 12; and 10,4 years.

Data used for this case:

Parameter	Home Charging	V2G	Unit
Electric vehicle price	30000	30000	[€]
Electric vehicle maintenance	300	300	[€/year]
Electricity price	0,2	0,2	[€/kWh]
Price per grid connection	100	150	[€/year]
Price of charger	1000	1000	[€]
Charger maintenance	100	100	[€/year]
Annual driving distance	20000,0	20000,0	[km]
Consumption	16,0	16,0	[kWh/100km]
Vehicle battery capacity	40,0	40,0	[kWh]
Annual consumption	3200,0	3200,0	[kWh]
Charging efficiency	0,9	0,9	[-]
Consumption daily	8,8	8,8	[kWh]
Connection to charger	365	365	days
Discharge power	-	5,0	kW

Table 6. – Costs and consumption data assumptions

All these data are based on Nissan Leaf specification and approximate prices of electricity and maintenance.

Peak Load Shaving 1 hour	**Home Charging**	**V2G**	**Unit**
End of Life Battery Threshold	**20**	**20**	%
Project Duration	5,5	5	[year]
Revenue	-	2,9	[€/hour]
Annuity Home Charging	0,23	-	-
Annuity V2G	-	0,25	-
Parameter	**Home Charging**	**V2G**	**Unit**
V2G hours spent per day	-	1	
Number of V2G hours per year	-	365	h/year
Total revenue per year	-	1059	[€]
Total revenue per vehicle life	-	5293	[€]
Price of charging per year	711,1	1116,7	[€/year]
Price of charging per vehicle lifetime	3911,1	3555,6	[€]
Total charging price	3911,1	290,8	[€]
Fixed costs per project life	2100,0	2250,0	[€]
Sum	6011,1	2540,8	[€]

Table 7. – Calculations based on EoLBT 20%

In this table we can see that when providing V2G services, the final sum of fixed costs and price per charging combined is significantly decreased by the V2G revenue and offset by the shortened lifetime of the vehicle.

The revenue is set up to be paid for every hour in which the service of Peak Load Shaving is provided. With such data, economic comparison can be established.

Firstly, the NPV (Net Present Value) of both approaches is evaluated. In this case the NPV does not provide the decision point concerning the minimum profitable revenue for the V2G solution. NPV is negative due to non-existent, or very low income whilst charging the vehicle. The EV vehicle in this study is not set up to bring explicit economic benefits.

$$NPV = \sum_{t=0}^{n} \frac{\mathrm{CFt}}{(1+r)^t}$$

Due to different project durations, comparison must be established regarding the level of RCF (Residual Cash Flow) which would be suitable to compare projects in this case. For this purpose annuity must be calculated regarding project duration and discount.

$$a = \frac{q^n \cdot (q-1)}{(q^n - 1)}$$

$$RCF = a \cdot NPV$$

$$q = (r + 1)$$

NPV … Net Present Value

RCF … Residual cash flow

a … annuity

CF_t … Cash flow per year

n … Duration of the project

r … discount value

A major parameter in analyzing applications of the V2G solution is the battery degradation which directly influences its capability to serve as bidirectional energy flow medium. The EoLBT parameter specifies how long can the battery successfully act in a V2G connection with acceptable impact on the drivers needs and total battery capacity allocated to providing such services. The EoLBT parameter directly influences the project duration.

This simplification helps to visualize the correlation between revenue and RCF. This helps to show what is the main advantage of considering an application of the V2G approach and what must be the minimal revenue which is paid to the vehicle owner. In this thesis the calculations are executed for illustration purposes and provide one of the possible models which can be used in later studies focused on more detailed definition of the revenue.

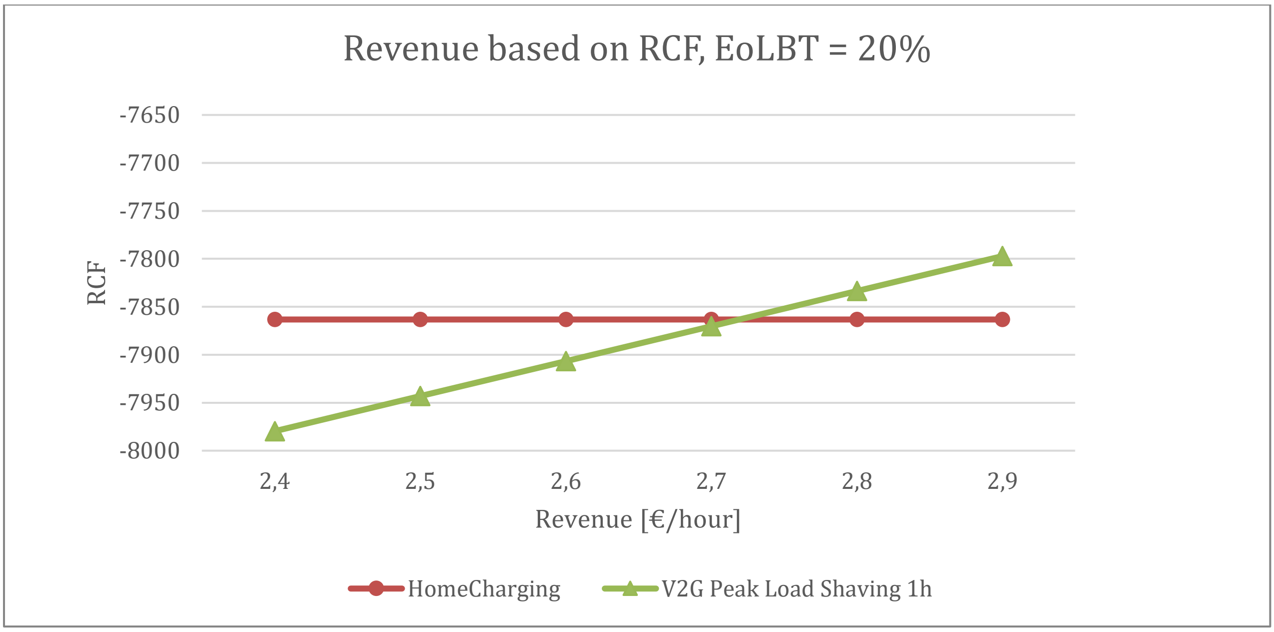

Figure 13. – Minimal V2G Revenue based on RCF and End of Life Battery Threshold set up to 20%

In our scenario, the minimal revenue for this case must be above 2,72 €/hour.

Typically, the End of Life Battery Threshold for an EV can be expected to be 30%. In Nissan Leaf with 40kWh of battery capacity, remaining capacity would therefore be 28kWh which translates to approximately 175 km of total mileage.

In such case, depending on the time spent providing Peak Load Shaving service, the revenue for one vehicle supporting the grid for 1hour is calculated to be 2,21 €/h, 2hour to be 2,09€/h and 3 hour to be 2,03€/h.

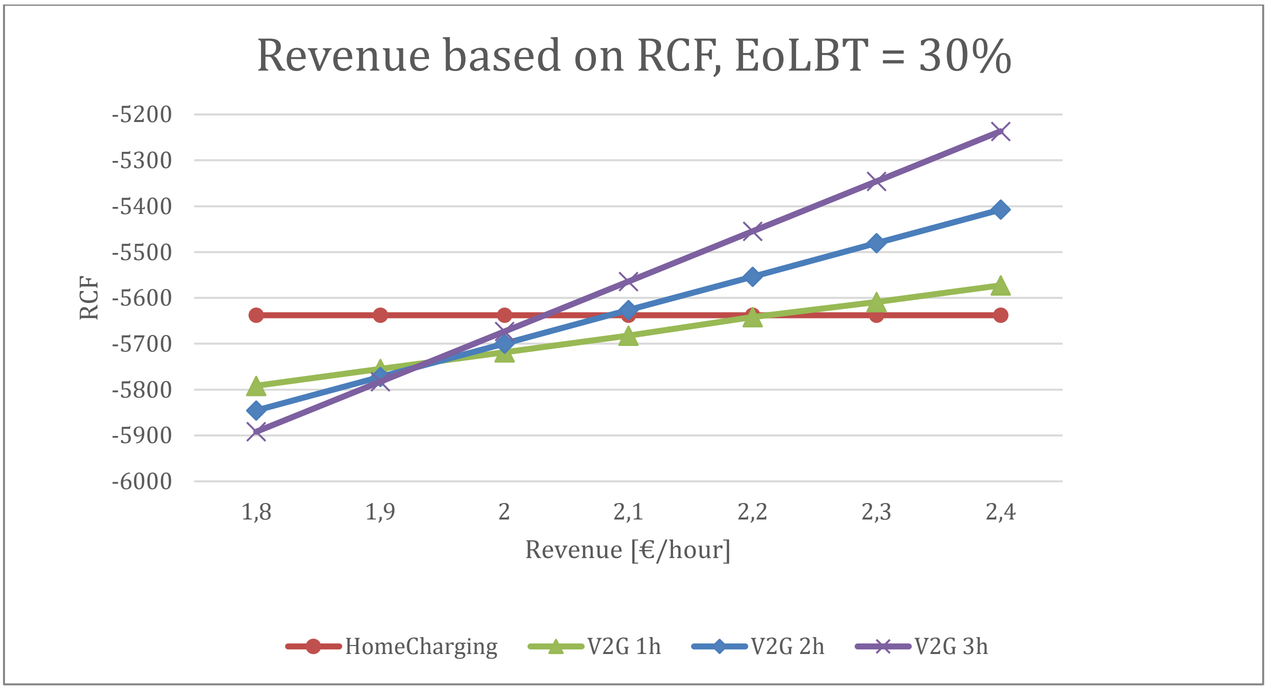

Figure 14. – Minimal V2G Revenue based on RCF and End of Life Battery Threshold set up to 30%

In a scenario of 40% EoLBT, Revenue can to be much lower due to longer project lifetime. In this scenario, the driving capacity at the end of project would be 24kWh. In a 1hour case, Minimal revenue is expected to be 1,95 €/hour, 1,7 €/h in a 2hour case and in a 3hour case 1,72 €/hour.

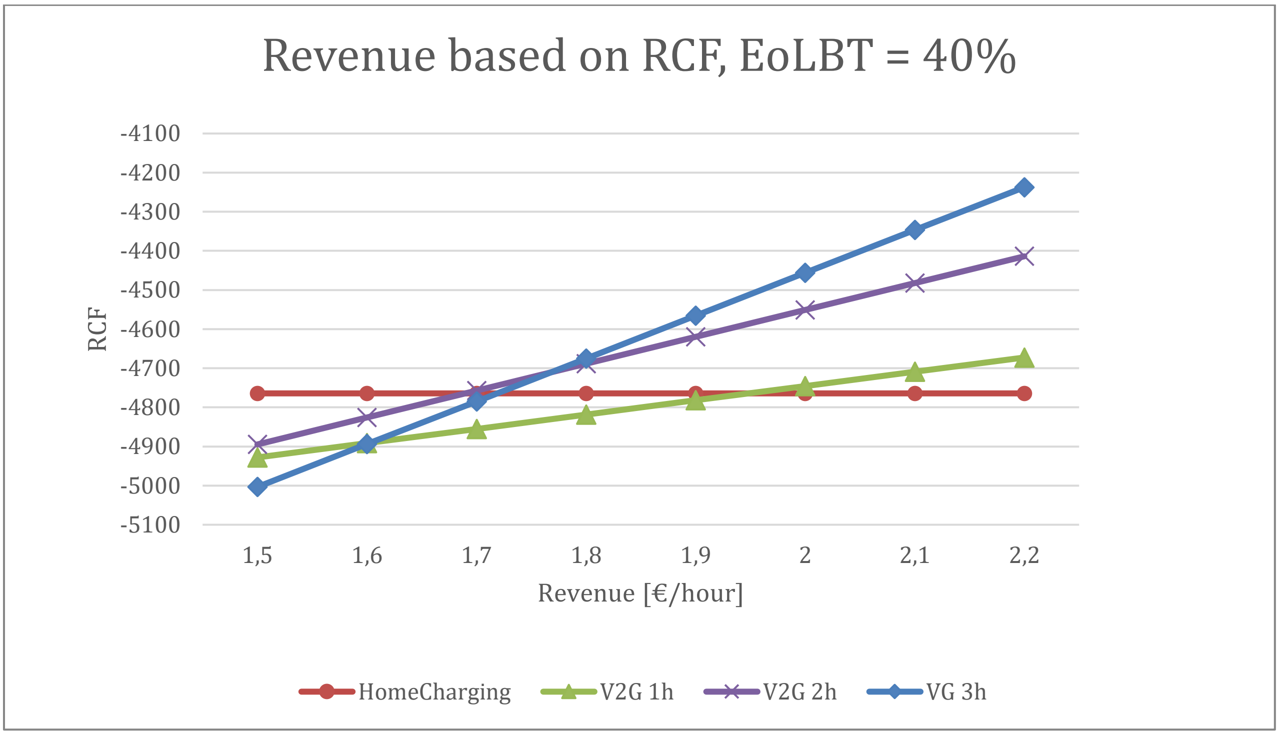

Figure 15. – Minimal V2G Revenue based on RCF and End of Life Battery Threshold set up to 40%

6.3.2 Other Ancillary services

V2G mode can provide not only Peak Load Shaving but for example also Frequency Regulation or Net Load Shaping. Frequency Regulation has similar negative effect on the battery degradation as in the case of Peak Load Shaving. Figure 16. shows how is the battery capacity influenced in several use cases of Frequency Regulation. The same calculations can be evaluated and compared against each other.

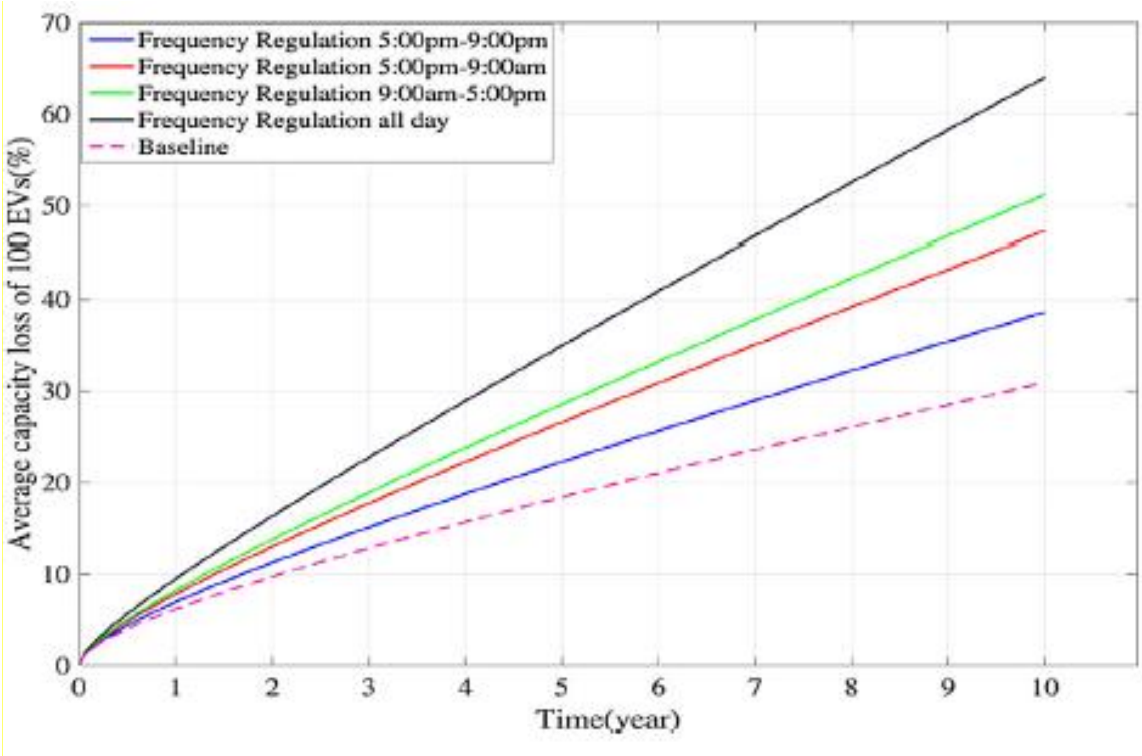

Figure 16. – Average 10-year battery degradation of 100 EVs for providing V2G frequency regulation with different regulation hours [37]

It should be noted that results shown in the graph above do not have to be relevant for the daily grid service support. The necessity of Frequency Regulation, as mentioned in a previous section, might occur 20-200 times per year. That assumption yields final difference in battery degradation within 31,88–36,01%. Average degradation of the battery pack, according to the study [37], from which these results originate, will be 0,0023% per 2hours of Frequency Regulation event.

Given the scope of this thesis, these cases are not described and evaluated in detail. Future studies might explore these opportunities using the underlying data.

6.3.3. Ancillary services remuneration

Subjects which provide AnS should be remunerated for the compensation of grid instabilities. Operational management is a responsibility of the respective grid operator which should also address the required specifications of upstream grid operators. TSO must then ensure system stability and cooperate also with other TSOs involved in the integrated European grid. Expansion of RES causes high power load fluctuations and grid instability, therefore a new approach to providing Ancillary Services must be applied, involving all possible technologies and resources available [38]. This thesis focuses on one example, a virtual battery composed of electric vehicles.

Minimal remuneration is calculated considering the number of vehicles (100 in our case), minimal revenue per hour and number of hours spent providing AnS. Figure 17. shows how expensive it would be if all vehicles provided its V2G services every day as a function of the number of daily service hours and the EoLBT parameter. In the first case where EoLBT was selected to be 20%, only one case, 1hour, was evaluated due to the low number of EV´s viable years. The lowest expenses can be seen in the case where EoLBT parameter is set up to be 40%, with EV estimated to be functioning 10 and more years, based on number of hours providing AnS.

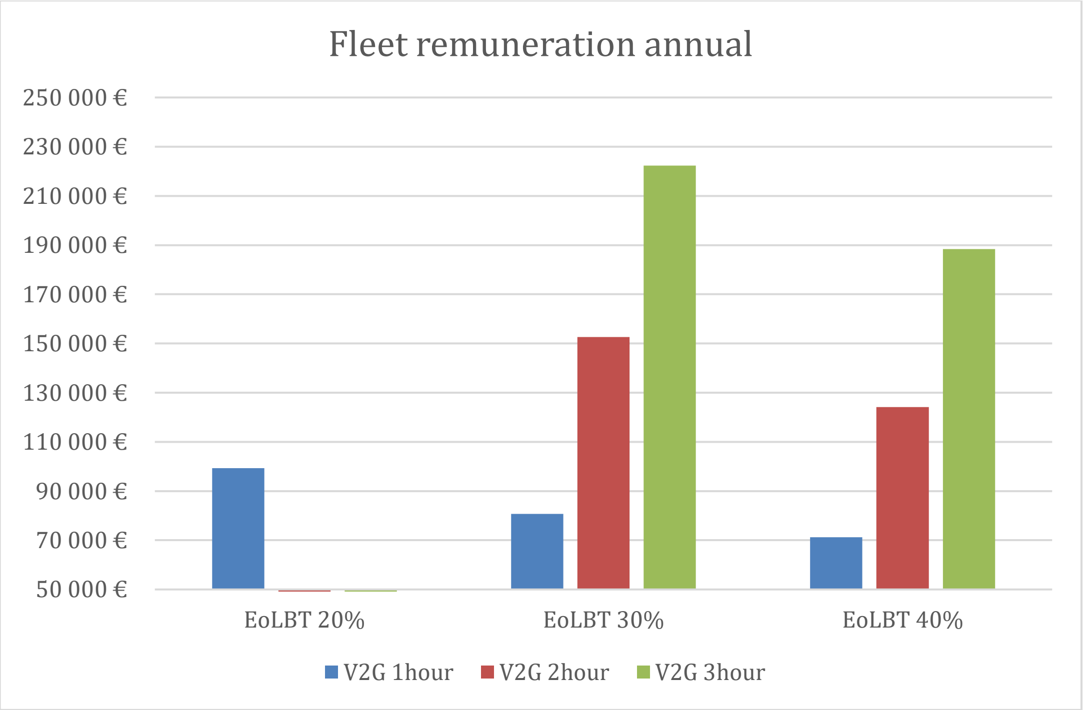

Figure 17. – Calculation of fleet remuneration annually

When Peak Load Shaving is provided by the entire vehicle fleet at the same time, maximum power output in our case is stated to be 500 kW, i.e. 1 hour of service provisioning equals to supplied energy of 500 kWh. According to this statement, Table 8. shows number of MWh provided annually.

EoLBT	20%	30%	40%	Unit
V2G 1hour	182,5	182,5	182,5	MWh
V2G 2hour	-	365	365	MWh
V2G 3hour	-	547,5	547,5	MWh

Table 8. – Number of MWh provided by fleet of electric vehicles

Actual costs of Ancillary Services can be compared to the data computed above to find if providing such service is profitable in the selected region.

This case serves to illustrate additional scenarios, its further evaluation is however beyond the anticipated scope of this thesis. This thesis could be extended using more specific data and is expected to be suitable for further study of V2G profitability.

6.4 Blockchain relevance in charging price

The focus of a V2G approach is to control the interaction between connected EVs and the grid. Traditional scheme is divided into three sections, centralized, switched and decentralized. The centralized control model gives rights to a central authority to schedule strategy of charging/discharging EVs in the areas of control need. However, this process can struggle with the problem of multi-objective optimization. Simply forcing all EVs to immediately charge or discharge in the local area might cause grid disbalance. Meaning power demand of the grid does not have to be solved at the same time. Furthermore, EV owners might be less interested in yielding control over their vehicles to a distant, centralized authority which is not fully aware of their individual needs in each moment due to privacy concerns.

On the other hand, a distributed solution considering Blockchain could be designed for security, privacy and payment transaction requirements in distributed energy switching systems. This model adopts the Blockchain as a concrete implementation scheme of a distributed control model whilst combining synchronization and real-time response advantages. Smart contracts are indispensable in controlling interactions of the EVs and the charging fleet, the grid and the charging pile, thereby achieving overall control at the code level [31]. Blockchain is the technology which can provide savings in current model solution.

To illustrate, Porsche Digital Lab in cooperation with the utility Vattenfall explored a design combining Blockchain and AI (Artificial Intelligence) to support “mobile virtual power plants” from the perspective of EV drivers and their communities. An Intelligent software organizes the charging of all connected vehicles according to their owner´s usage profiles to ensure that every vehicle is charged enough in time of need [39].

In another example, Bosch works with the utility EnBW (Energie Baden-Württemberg AG) to develop economic agents using AI to negotiate on behalf of EVs and the drivers with the EV chargers, using Blockchain “as the technical basis for coordinating EV charging with any energy provider” [40].

In a third example, the Dutch-German grid operator TenneT works with IBM and energy supplier Vandebron using Blockchain and over 150 Tesla EVs to "make bids every day on TenneT's regulating and reserve capacity market", with the bids actually activated by TenneT. This solution is contributing to the maintaining the balance of the grid in real-time. Further development should bring the opportunity to connect any type of vehicle with possibility to provide power regulation or automatic Frequency Restoration Reserve (aFRR) [41].

6.4.1 Model design

With the rising number of EVs operating in the grid, the importance of control and organization of structural relations of interaction between EVs increases. The concept of a charging fleet is significant in developing a relevant power system with goals of achieving high efficiency and "clean" approach. The P2P Blockchain structure for securing of transactions and transparent authenticating mechanism is a relevant candidate for implementing this concept. Suggested solution consists of several parts: Physical fleet of EVs, P2P charging pile (virtual fleet), transaction network (based on Blockchain) and the power grid. EVs participate in the system as a virtual battery, which is being charged or discharged. The P2P charging pile is the dispatching energy center for the whole system. Each charging pile acts as a single node which receives the demand information from the power grid in real time and dispatches corresponding EVs to charge or discharge, generating transaction records based on the EV behavior which are then immutably written to the Blockchain [31].

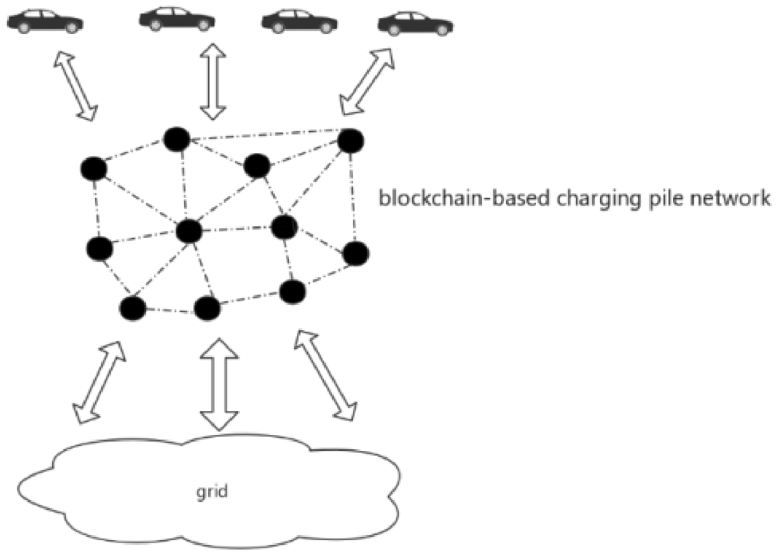

Figure 18. – System architecture [31]

The power grid can interact with the charging pile and if necessary the corresponding energy supply is released also with all relevant information. This is achieved with a programmable charging point. The execution process is shown in the next Figure.

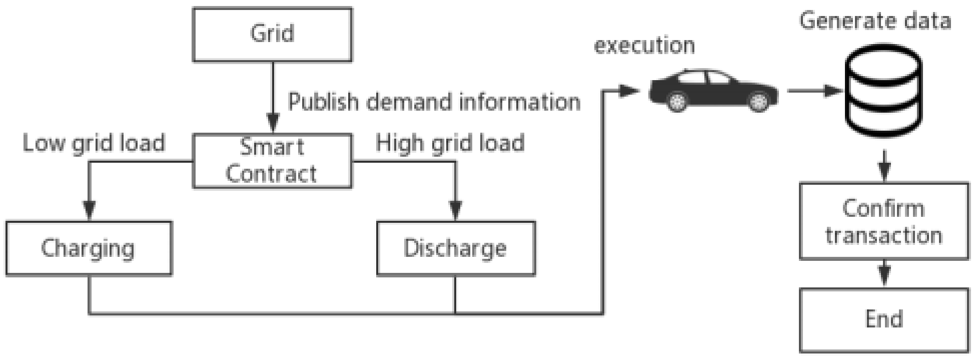

Figure 19. – System flowchart [31]

Blockchain serves as a basis for the entire system and is responsible for every transaction record that occurs throughout the control model. Each charging and discharging event forms a separate transaction record, which is saved in the Blockchain itself by the charging pile software layer and is updated real-time. This model is described in Figure 20. This approach can bring high costs savings compared to traditional models considering operating and maintaining data storage and data processing, while providing immutable records auditable by any authorized party.

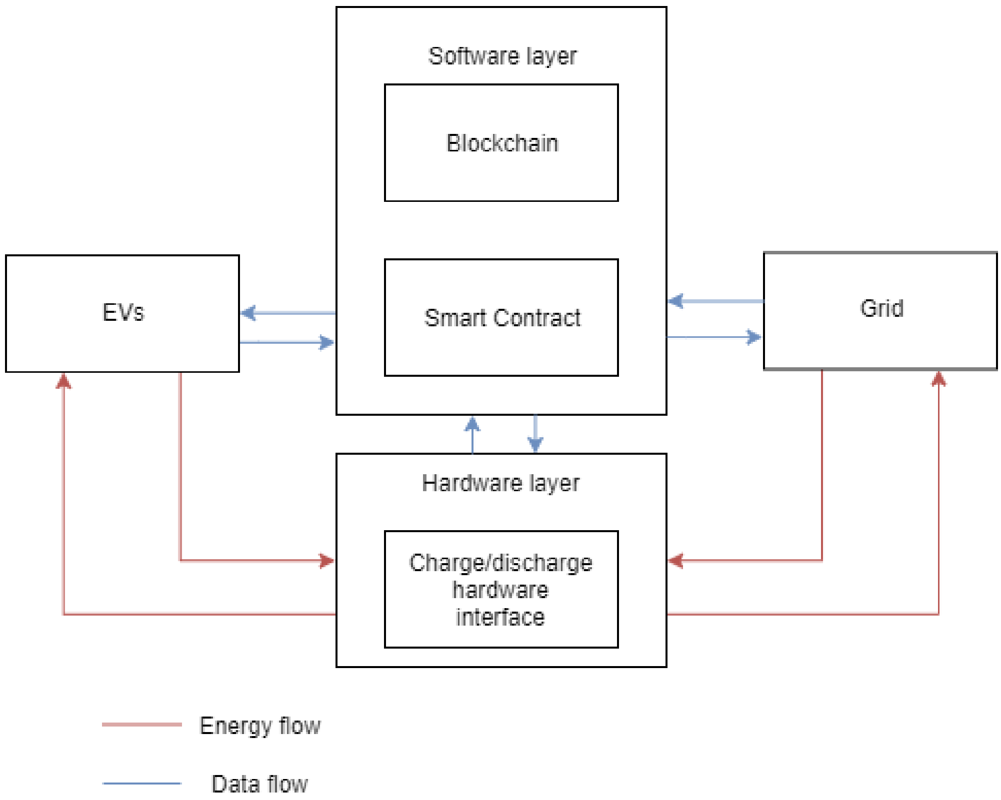

Figure 20. – Interaction between EVs, single charging pile and the grid [31]

When an EV is connected to the charging point, the software layer collects relevant status data from the vehicle and can also take into account owner's special needs. Hardware elements only accept instructions from the software layer and provide charging or discharging, reporting all data about the event afterwards.

6.5 Other Blockchain benefits

Calculations made by the major DSO in France, Enedis (formerly ERDF), indicated that for every 1 million of new electric vehicles globally traveling, the cost of low voltage grid reinforcement to enable charging in home chargers would be €200 million with even higher costs for public charging infrastructure. Calculations also indicated that Smart Charging could reduce the incurred costs by 100% in home charging case and almost 50% in public charging. Smart Charging can help in optimizing power demand and thus grid operation, which leads to lower additional investments needed to optimize the grid. It also helps with flexibility and information provision to grid operators about power consumption [42].

When information is exchanged efficiently, utilization of assets can be improved, trust enhanced, operation costs and further investments can be reduced. The concept of Distributed Ledgers, Smart Contracts and the P2P approach enable multiple parties to share safely and trustfully the relevant information, optimize and automate processing of their assets and settle the transactions. Included parties and their benefits are [42]:

- **Customers** – lowering costs of charging by optimizing use of their EV, based on vehicle availability being rewarded while providing AnS to the grid via bi-directional chargers,
- **Charging pole operators** – increasing utilization of their assets and improving customer experience,
- **Electricity suppliers** – facilitation of provided wholesale power and additionally responding to demand needs through online information shared on distributed ledgers,
- **Aggregators** – providing information flow and forecast of supply and demand and executing the demand response command to the charging pile network which is based on data of DSO and TSOs,
- **Distribution grid operators** – who benefit from future power demand forecast, indication of grid constraints whilst providing commands to change the behavior of assets to EV owners and aggregators, in order to optimize grid stability and to prevent extreme situations or defer grid-update costs,
- **Transmission grid operators** – who facilitate provision of wholesale power, ancillary and balancing services and improving grid stability based on future power demand.

All parties mentioned can decrease their transaction costs by using certain Blockchain-settlement technology, which can be enabled also on the micro-transaction level and in real-time. The concept of coordinated and automated agreement realization, smart contracts and decentralized data feeds could also help in automating the transactions processing, lowering back-office costs and the need for extra operational capital.

The emerging solution of Smart Charging, based on Blockchain technology, could help to balance the market approach whilst optimizing the nature of decentralized transaction systems. This would help to improve customer experience, integrate RES into energy markets and build open standards to provide a foundation of shared mobility infrastructure available across EU and all around the world.

7. Conclusion

Blockchain-based implementations are maturing and becoming relevant for various industries in use cases involving a diverse set of transaction partners who might not trust their counter-parties.

This evolution is illustrated by the fact of total amount of investments committed worldwide to this technology. The European Investment fund for example released in 2019 a budget aiming to boost innovation in AI and Blockchain. The first phase of this project will make available 100 million euros in 2020 to support companies working in this sector [43].

The most powerful governments worldwide are advocating at their most senior level for greater use of Blockchain. For instance the Chinese president Xi Jinping stressed expediting the development of the Blockchain technology and innovation-driven industrial development with "*efforts to strengthen basic research and boost innovation capacity to help China gain an edge in theories, innovation and industries of the emerging field*" [44].

Also energy-related Blockchain implementations enter their commercial phase, for example EDP Group (global energy company) and EI Corte Inglés (biggest department store group in Europe) are teaming up to identify in real-time the origin of renewable energy consumed by El Corte Inglés shopping centers in Malaga, Seville and Madrid [45]. Similar initiatives can be observed in the automotive sector, with examples mentioned earlier in this thesis.

The focus of this thesis was however mostly on defining the formula for the price of EV charging, when Blockchain is playing its role. Charging of the electric vehicle itself is a complex process involving vehicle´s battery, charging equipment and the grid, to which is vehicle being indirectly connected while charging. Blockchain could be applied on various levels of the charging process. In our study, Blockchain is considered to be a part of the transaction layer when vehicle is being used for Vehicle-to-Grid (V2G) and receives revenue based on the amount of hours spent while providing Ancillary Services.

Providing such services using any kind of Li-ion battery shortens its life which plays a crucial role in evaluating feasibility of the V2G approach. Based on the data provided by the simulation software V2G-Sim developed by the Lawrence Berkley National Laboratory [46], battery degradation data of the Nissan Leaf while providing Peak Load Shaving services was used to estimate the negative effects inflicted on the battery as a function of the number of hours per day providing grid support services. Net Load Shaping and Frequency Regulation services were not evaluated in detail in this thesis, but could be explored in a similar process of calculation.

Based on data from these simulations, the minimal revenue can be calculated for the V2G bi-directional mode and compared with the classical approach of EV which is being only uni-directionally charged during its lifetime. These data can be used in further studies and confronted with remuneration of specific Ancillary Services.

Blockchain plays a role in the definition of the charging price formula, but it is not involved in the final price of charging explicitly. To achieve an effective transformation and change in the existing automotive and energy industry, electric vehicle must be considered as an active element of the grid and not just a passive electricity consumer. To successfully achieve that, Blockchain can be considered as a part of the smart solution which should be involved in future development of the Smart Charging approach. It should be noted that Blockchain itself cannot help or solve all the issues and constraints mentioned in this thesis without complementary digital technologies like Artificial Intelligence, IoT, Smart Metering, etc. It is a part of the puzzle which together creates an environment suitable for all the vehicles connected to the grid.

Due to the increasing number of electric vehicles in use, certain level of charging coordination must be applied to achieve grid stability. Similar development can be observed in many other industries. The upcoming generation of digital solutions will help with improved coordination across those industries, and Blockchain seems to be a valuable building block which will facilitate transactions among all actors, human and machine.

References

1. [Online] [Cited: May 1, 2019.] https://en.wikipedia.org/.

2. [Online] [Cited: May 1, 2019.] https://en.bitcoinwiki.org/.

3. *Bitcoin price, charts, market cap, and other metrics.* [Online] [Cited: May 10, 2019.] https://coinmarketcap.com/currencies/bitcoin/.

4. *Blockchain in Electricity: a critical review of progress to date.* [Online] [Cited: May 1, 2019.] https://cdn.eurelectric.org/media/3115/paper1_blockchain_eurelectric-h-CB8D6920.pdf.

5. *Blockchain Application Platform.* [Online] [Cited: May 15, 2019.] https://lisk.io/academy/blockchain-basics/how-does-blockchain-work/consensus-protocols.

6. *Porovnání produktů na výkup přebytku z fotovoltaické elektrárny pro domácnosti.* [Online] [Cited: June 27, 2019.] https://energetika.tzb-info.cz/elektroenergetika/17698-porovnani-produktu-na-vykup-prebytku-z-fotovoltaicke-elektrarny-pro-domacnosti.

7. *Blockchain, Transactive Grids, Microgrids, Energy Trading.* [Online] [Cited: May 28, 2019.] https://lo3energy.com/.

8. *The Brooklyn microgrid: blockchain-enabled community power.* [Online] [Cited: July 4, 2019.] https://www.power-technology.com/digital-disruption/blockchain/featurethe-brooklyn-microgrid-blockchain-enabled-community-power-5783564/.

9. *Využití blockchain technologie v energetice.* [Online] [Cited: July 5, 2019.] http://oenergetice.cz/technologie/vyuziti-blockchain-technologie-energetice/.

10. *BLOCKCHAIN BASED SOLUTION ENABLES P2P TRADING OF ELECTRICITY BETWEEN PROSUMERS.* [Online] [Cited: December 20, 2019.] https://www.ponton.de/launch-of-enerchainlocal/.

11. [Online] [Cited: July 20, 2019.] www.veridium.io.

12. [Online] [Cited: July 20, 2019.] www.voltmarkets.com.

13. *pv magazine International – Photovoltaic Markets and Technology.* [Online] [Cited: August 25, 2019.] https://www.pv-magazine.com/2018/11/12/singapore-launches-blockchain-based-renewable-energy-marketplace/.

14. *Harnessing blockchain to foster climate markets under the Paris agreement.* [Online] [Cited: December 15, 2019.] https://blogs.worldbank.org/climatechange/harnessing-blockchain-foster-climate-markets-under-paris-agreement.

15. *Blockchain pilot reveals potential of decentralised home storage systems for tomorrow's energy infrastructure.* [Online] [Cited: June 13, 2019.] https://www.tennet.eu/news/detail/blockchain-pilot-reveals-potential-of-decentralised-home-storage-systems-for-tomorrows-energy-infra/.

16. *Blockchain Technology in the energy transition.* [Online] [Cited: June 9, 2019.] https://kth.diva-portal.org/smash/get/diva2:1235832/FULLTEXT01.pdf.

17. *National Grid ESO partners networks, Electron for blockchain-powered DER asset register pilot.* [Online] [Cited: July 15, 2019.] https://www.current-news.co.uk/news/national-grid-eso-partners-networks-electron-for-blockchain-powered-der-asset-register-pilot.

18. [Online] [Cited: July 20, 2019.] http://shareandcharge.com/.

19. *Automobilky nejsou připraveny na pokuty za emise. Bude to znamenat konec malých vozů, píší Financial Times — ČT24 — Česká televize.* [Online] [Cited: July 20, 2019.] https://ct24.ceskatelevize.cz/ekonomika/2799308-automobilky-nejsou-pripraveny-na-pokuty-za-emise-bude-znamenat-konec-malych-vozu.

20. *Tesla Model 3: dojezd až 800 km, ale paradoxně u lite verze.* [Online] [Cited: July 20, 2019.] https://elektrickevozy.cz/clanky/tesla-model-3-dojezd-az-800-km-ale-paradoxne-u-lite-verze.

21. *V Evropě je skoro 6000 CCS nabíjecích stanic, každý den přibude pět nových.* [Online] [Cited: July 25, 2019.] http://www.hybrid.cz/v-evrope-je-skoro-6000-ccs-nabijecich-stanic-kazdy-den-pribude-pet-novych.

22. *How Long Does It Take to Charge an Electric Car.* [Online] [Cited: July 25, 2019.] https://pod-point.com/guides/driver/how-long-to-charge-an-electric-car.

23. *EV Charging Station Cost.* [Online] [Cited: May 15, 2019.] https://www.ohmhomenow.com/electric-vehicles/ev-charging-station-cost/.

24. *The basics of electric-vehicle charging infrastructure | McKinsey. McKinsey & Company | Global management consulting.* [Online] [Cited: April 4, 2019.] https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/charging-ahead-electric-vehicle-infrastructure-demand.

25. *Eight reasons why the future belongs to electro mobility.* [Online] [Cited: August 6, 2019.] https://www.elect-expo.com/en/electrifying-impulses/eight-reasons-why-the-future-belongs-to-electro-mobility/.

26. [Online] [Cited: August 10, 2019.] https://www.skoda-storyboard.com/cs/inovace/mobilita/dotace-na-nakup-nulova-dan-nebo-zadne-mytne-aneb-jak-podporit-e-mobilitu/.

27. *Motor Vehicle Production | ACEA - European Automobile Manufacturers' Association. ACEA - European Automobile Manufacturers' Association.* [Online] [Cited: June 10, 2019.] https://www.acea.be/statistics/tag/category/production.

28. *Reducing CO2 emissions from passenger cars.* [Online] [Cited: June 20, 2019.] https://ec.europa.eu/clima/policies/transport/vehicles/cars_en.

29. *Electric Vehicle Outlook 2019 | Bloomberg NEF. BloombergNEF | Bloomberg Finance L.P.* [Online] [Cited: July 5, 2019.] https://about.bnef.com/electric-vehicle-outlook/#toc-viewreport.

30. *Modeling Vehicles to Grid as a Source of Distributed.* [Online] [Cited: September 28, 2019.] https://www.mdpi.com/1996-1073/12/4/720/pdf.

31. *Distributed Electric Vehicle Control Model Based on Blockchain.* [Online] [Cited: August 25, 2019.] https://iopscience.iop.org/article/10.1088/1757-899X/486/1/012046/pdf.

32. *Comparing All 2019 Electric Vehicles. Electric Cars & Plugin Hybrids.* [Online] [Cited: August 8, 2019.] https://www.myev.com/research/buyers-sellers-advice/comparing-all-2019-electric-vehicles.

33. *Adequacy and flexibility study for Belgium 2020-2030.* [Online] [Cited: August 26, 2019.] https://www.elia.be/-/media/project/elia/elia-site/adequacy-studies/adequacy-studies/20190628_elia_adequacy_and_flexibility_study_2020_2030_nl_archive.pdf.

34. *Vehicle-to-grid regulation based on a dynamic.* [Online] [Cited: August 26, 2019.] https://www.elia.be/-/media/project/elia/elia-site/adequacy-studies/adequacy-studies/20190628_elia_adequacy_and_flexibility_study_2020_2030_nl_archive.pdf.

35. *Vehicle-to-grid service development logic and management formulation.* [Online] [Cited: September 15, 2019.] https://link.springer.com/article/10.1007/s40565-018-0464-7.

36. *System Perspectives on Electromobility.* [Online] [Cited: November 12, 2019.] https://www.researchgate.net/publication/264894400_System_Perspectives_on_Electromobility/figures?lo=1.

37. *Quantifying electric vehicle battery degradation from driving vs. vehicle-to-grid services - ScienceDirect.* [Online] [Cited: November 12, 2019.] https://www.sciencedirect.com/science/article/abs/pii/S0378775316313052.

38. *Ancillary services – Deutsche Energie-Agentur (dena).* [Online] [Cited: November 17, 2019.] https://www.dena.de/en/topics-projects/energy-systems/electricity-grids/ancillary-services/.

39. *Combining AI and Blockchain at Odyssey Hackathon.* [Online] [Cited: 12 12, 2019.] https://newsroom.porsche.com/en/porsche-digital/porsche-digital-odyssey-hackathon-ai-blockchain-porsche-digital-lab.html?_sm_au_=iVVSvFn6wWQQFW7523jRBKHsLv0sM.

40. *Cars that negotiate with charging stations.* [Online] [Cited: 12 12, 2019.] https://www.bosch.com/stories/dlt-cars-that-negotiate-with-charging-stations/?_sm_au_=iVVSvFn6wWQQFW7523jRBKHsLv0sM.

41. *TenneT: continuing with Blockchain after successful pilots.* [Online] [Cited: 12 12, 2019.] https://www.tennet.eu/news/detail/tennet-continuing-with-blockchain-after-successful-pilots/?_sm_au_=iVV0J72FsRZscFH523jRBKHsLv0sM.

42. *Freedom of Charging:.* [Online] [Cited: November 10, 2019.] https://cdn.eurelectric.org/media/2187/eurelectric_blockchain_platform_interim_report_-2017-030-0765-01-e-h-E3249329.pdf.

43. *EU Artificial Intelligence and Blockchain investment fund to invest 100 million euros in startups in 2020.* [Online] [Cited: December 10, 2019.] https://ec.europa.eu/digital-single-market/en/news/eu-artificial-intelligence-and-blockchain-investment-fund-invest-100-million-euros-startups.

44. *Xi stresses development, application of blockchain technology.* [Online] [Cited: December 10, 2019.] http://www.xinhuanet.com/english/2019-10/25/c_138503254.htm.

45. *The EDP Group and El Corte Inglés are launching a ground-breaking project.* [Online] [Cited: December 5, 2019.] https://www.edpr.com/en/news/2019/12/04/edp-group-and-el-corte-ingles-are-launching-a-ground-breaking-project.

46. *V2G-Sim.* [Online] [Cited: October 28, 2019.] http://v2gsim.lbl.gov/.

47. *What is backdoor (computing).* [Online] [Cited: July 25, 2019.] https://searchsecurity.techtarget.com/definition/back-door.

List of abbreviations

AI – Artificial Intelligence

AC – Alternating current

AnS – Ancillary services

aFRR – automatic Frequency Restoration Reserve

BEV – Battery Electric Vehicles

BTC – Bitcoin

CF – Cash Flow

CO2 – Carbon Dioxide

CP – Charging Point

CPO – Charge Point Operator

DC – Direct Current

DCFC – Direct-Current Fast Charger

DOD – Depth of Discharge

DSO – Distribution System Operator

EnBW – Energie Baden-Württemberg AG

EoLBT – End of Life Battery Threshold

ERDF – European Regional Development Fund

EV – Electric Vehicle

EVSE – Electric Vehicle Supply equipment

GSO – Grid System Operator

HEV – Hybrid Electric Vehicles

ICE – Internal Combustion Engine

ICO – Initial Coin Offering

ID – Identifier

IP – Internet protocol

IT – Information Technology

KWh – Kilowatt hour

MB – Megabyte

MWh – Megawatt hour

NPV – Net Present Value

P2P – Peer-to-Peer

PBFT – Practical Byzantine Fault Tolerance

PFC – Primary Frequency control

PHEV – Plug-in Hybrid Electric Vehicles

PoA – Proof of Authority

POC – Proof of Concept

PoS – Proof of Stake

PoW – Proof of Work

RES – Renewable Energy Systems (Sources)

RCF – Residual Cash Flow

SOC – State of Charge

TSO – Transmission System Operator

TTP – Trusted Third Party

USD – United States Dollar

V2G – Vehicle-to-Grid

V2H – Vehicle-to-Home