

# Developing an integrated methodological guide for the utilisation of decentralised assets and blockchain for grid balancing.

*Providing automatic Frequency Restoration Reserve from an aggregation of electric vehicles.*



*'The start of a new beginning'. Image by NASA.*

## *Master's Thesis Energy Science*

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*“ It is paradoxical, yet true, to say, that the more we know, the more ignorant we become in the absolute sense, for it is only through enlightenment that we become conscious of our limitations. Precisely one of the most gratifying results of intellectual evolution is the continuous opening up of new and greater prospects.”*

*~ Nikola Tesla*

## Preface

Paradigms are shifting, from centralised to decentralised, from linear to circular and from conventional to sustainable. Today, the opportunity exists to design systems of the future, such as the energy system, in a cleaner, more efficient and more sustainable way. I feel more than privileged to have been able to get a grasp of the thrilling possibilities during my time at the Utrecht University. This Master's thesis does not only feel as the result of the past months, but merely as a logic outcome of everything I have learnt (to value) during my time as a student and even before.

I am grateful to many people, whose support strongly improved the quality of my work. Starting at the academic side, I want to thank Ioannis. Your supporting attitude, academic, and detailed perspective and deep expertise regarding electricity markets and aFRR related processes enhanced the robustness of this thesis significantly. I also want to thank Tarek for his new-born enthusiasm and positivism. Due to your extensive knowledge on blockchain, you and Ioannis were a very complementary duo. Wouter, as my third supervisor, you too deserve a big thanks for the helpful meetings and valuable feedback.

At TenneT side, I would also like to thank some people. Emma, you have a rare complete set of qualities. You combine a mathematical perspective, with strong social skills, tonnes of enthusiasm and admirable persistency. I could not have wished for a better supervisor. Henrie, I found it inspiring to see how you prioritise and how your vision concentrates around the well-being and safety of your team and TenneT in general. Our meetings at the beginning of this trajectory pushed me in using my imagination and setting the bar rather high. Lastly, I want to thank Elmar Dongelmans, with whom I had many thought-provoking sessions about how the future energy system, enabled by blockchain technology, could look like. You are empowered by thinking in conceptual opportunities rather than in operational obstacles, please do not let this gift slip away.

It has been fascinating to think and write about the future possibilities originated from the new combination of different technologies which will probably reshape our society and lives significantly. On one hand, the rise of electric vehicles seems inevitable and on the other hand the features of blockchain and other types of distributed ledger technology offer huge potential for future Internet of Things and subsequently Energy of Things opportunities. The beauty of this subject lies for me in the symbiosis of highly interesting technological matter and the opportunity to use this technology to create a greener and smarter world.

Somehow, I am sad to hereby finish my period of time as a student, as I genuinely loved the intellectual evolution and even the realisation of ignorance after obtaining new insights, so accurately described by one of the most genius inventors and physicists of all time. This quote relates to both my evolution as a person as the evolution of the energy system. Luckily, great prospects open up and whereas my time as a student at university ends, I will, very fortunately, remain to be a student of life.

*B.J.D. (Bart) Holthuisen  
Utrecht, July 2018*

## Abstract

The energy system is in transition from a centralised demand driven system to a decentralised supply driven system due to an increasing penetration of renewable energy sources (RES). This increasing share of RES results in more fluctuations at the supply side, while less conventional power plants will be available in the future to provide ancillary services. This results in the need to unlock flexibility at the demand side. Therefore, TenneT, the Dutch Transmission System Operator (TSO), initiated a pilot in which a fleet of electric vehicles (EVs) is deployed for the provision of automatic Frequency Restoration Reserve (aFRR). In addition, blockchain technology is used to gather more insights in whether this technology could have added value in a future energy system. In this thesis, the data from the pilot is analysed to assess the technical feasibility of aFRR provision by EVs. Besides, the value of blockchain technology for this specific application is considered. The thesis ends with proposing a blockchain concept that could be used for various flexibility related challenges in the future.

The thesis shows that EVs respond to aFRR activation adequately during several activated bids regarding requirements such as the minimum regulation rate and activation time. Based on the data in the pilot, it could be concluded that it is technically feasible to provide aFRR with EVs. Regarding blockchain technology different advantages for the specific application are determined. Blockchain technology can increase the integrity of the input data, which results in more reliable data logging. Besides, automation can be achieved via the deployment of smart contracts, which also results in transparency amongst stakeholders.

With respect to improvements towards the future, an alternative aFRR verification method is designed and proposed. The aim of the method is to (partially) automate the verification process which is currently executed manually and visually. This could reduce the workload of the TSO in a potential future energy system in which aFRR is provided by a myriad of decentralised assets. Lastly, a blockchain design is proposed in which all required transactions are stated and described in order to go automatically through all phases of the aFRR process (i.e., planning, real-time operations and verification and settlement). In addition, it is elaborated on how the blockchain design could be expanded by integrating (future) relevant stakeholders such as Distribution System Operators and Balance Responsible Parties in order to achieve a system level solution.

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## Nomenclature

ACE	Area Control Error
aFRR	automatic Frequency Restoration Reserve
BRP	Balance Responsible Party
BSP	Balancing Service Provider
CC-CV	Constant Current – Constant Voltage
CP	Charging Pole
CFT	Cross-Fault Tolerance
DLT	Distributed Ledger Technology
DoD	Depth of Discharge
DSO	Distribution System Operator
DAG	Directed Acyclic Graph
E-programme	Energy Programme
EV	Electric Vehicle
FCR	Frequency Containment Reserve
FVR	Frequentie Vermogens Regeling
GCT	Gate Closure Time
ICT	Information Communication Technology
IoT	Internet of Things
ISP	Imbalance Settlement Period
LFC	Load Frequency Control
M2M	Machine-to-Machine
mFRR	manual Frequency Restoration Reserve
MRP	Metering Responsible Party
PACE	Process Area Control Error
PBFT	Practical Byzantine Fault Tolerance
PoS	Proof of Stake
PoW	Proof of Work
RES	Renewable Energy Sources
RTU	Remote Terminal Unit
SoC	State of Charge
TSO	Transmission System Operator
V2G	Vehicle to Grid
vRTU	virtual Remote Terminal Unit

# 1. Introduction

## 1.1. Context

The structures that form the basis of the energy system are changing in a fundamental way. The preceding centralised, demand driven and vertical architecture is being transformed into a decentralised, supply driven and a more a horizontal one, accompanied by the shift from conventional power plants towards renewable energy resources (RES) such as wind and solar. These paradigm shifts pose challenges on the reliability and robustness of the energy system. For instance, the intermittent character of RES results in increasing fluctuations at the supply side of the power system [1], which complicates the task to maintain the real-time power balance on the electricity grid. To deal with these fluctuations, flexibility is needed. In this thesis, flexibility is defined as “the modification of generation injection and/or consumption patterns in reaction to an external signal (price signal or activation) in order to provide a service within the energy system” [2].

In the traditional energy system, flexibility is usually provided by a couple of large centralised assets such as conventional power plants which are ramped up or down to provide ancillary services in order to restore the grid balance. In the future energy system, in which conventional power plants will (partly) be phased out, unlocking flexibility at the demand side using decentralised assets is considered as an important factor for an effective energy transition [2], [3], [4].

Parallel to the increasing importance of enabling flexibility from decentralised assets, there have been many developments in the field of information and communication technologies (ICT) during the last years. Predominantly, the advent of blockchain technology proposes a fundamentally different way of how information is stored, shared and verified. The essential idea, is to create a decentralised environment in which no third or central party is solely in control of transactions and data [5]. In combination with the transparent, verifiable and permanent character of the technology, blockchain has the potential to shape and support the evolution of the energy system from a centralised and vertical architecture to a decentralised and more horizontal one. For instance, blockchain could play a role in enabling demand side management with decentralised assets [6].

## 1.2. Problem definition

However, providing flexibility with decentralised assets is escorted by different challenges compared to providing flexibility with centralised assets. In addition, it is complicated to determine the real added value of blockchain, considering the technology to be in a phase of ‘irrational exuberance’ [7]. To gain more insights into these two topics, the Dutch transmission system operator (TSO), TenneT, the responsible party for amongst others power balancing, has set up a pilot in the Netherlands. In this pilot the charging process of a fleet of electric vehicles (EVs), currently only consisting of Tesla cars, is controlled by the aggregator Vandebron. This aggregator acts as a balancing service provider (BSP) and provides automatic frequency restoration reserve (aFRR), which is used for maintaining the real-time power balance on the electricity grid [8]. Besides, blockchain technology is used in this pilot to manage data and transactions in a decentralised, verifiable and permanent way.

The aim of the pilot is twofold. On one hand, the TSO wants to gain more insights in whether EVs are suitable decentralised assets to provide aFRR and on the other hand the goal is to retrieve more information about the advantages of using blockchain for data management and verification purposes. Hence, two aspects in this pilot can be identified, i): enabling the provision of ancillary services with decentralised assets (i.e., controlling the charging process of a fleet of EVs) and ii): determining the added value of blockchain technology for this application.

In previous studies these different aspects have been assessed separately. A review of the potential role of electric vehicle fleet management in the future energy system for different applications is provided by [9], showing potential for grid balancing. In [10] the opportunities, challenges and possible solutions for power balancing through aggregators and decentralised assets are determined. This research shows that no available platform has been identified yet to enable the provision of ancillary services on a local level. General advantages of blockchain technology, like transparency and immutability, are discussed in [11], [12]. Nevertheless, a practical implementation of EVs providing aFRR is new and so is the combination with blockchain. Altogether, it is yet unclear if and how EVs, aFRR and blockchain should be combined to enable flexibility with decentralised assets on a larger scale.

### 1.3. Research aim, sub questions and methodology

In this thesis the practical implementation of EVs and blockchain for aFRR provision is analysed from a theoretical perspective. The outcomes of the thesis are expected to shed light on the functioning of the current investigated pilot and on potential adaptations to improve and expand the concept. The research aim is formulated as follows:

*Assessing in the set-up of the investigated pilot whether EVs, in combination with blockchain technology, are suitable to provide aFRR and, if so, proposing an integrated solution for the future.*

To achieve the research aim, several sub questions are formulated. Sub question 1 is formulated as:

#### 1. *Is the utilisation of EVs for aFRR provision technically feasible?*

This question is answered by analysing the data of the investigated pilot. This includes data analyses in Python regarding the responses of the individual assets as well as of the pool of EVs in case of aFRR activation (e.g., change in power output, response time and ramp up/down rate). This is compared to the aFRR requirements to assess whether EVs can technically meet these requirements. In addition, analyses are conducted to assess the order of magnitude regarding the number of required assets in case of scaling up the concept. Answering this sub question results in obtaining a better insight in whether EVs are suitable assets to provide aFRR.

The second sub question relates to the blockchain component of the investigated pilot and is formulated as:

2. *What is the added value of blockchain technology for the utilisation of EVs for aFRR?*

To answer this question, the functioning and features of (different variants of) blockchain technology are described and assessed. Furthermore, the data that is registered on the blockchain is analysed regarding level of resolution and frequency to assess whether this matches with the technical performance of blockchain (e.g., transaction speed and stability).

The third sub question relates to the future relevance of this thesis and the exploration regarding improvements and expansion of the concept and is formulated as:

3. *What are possible improvements with respect to the investigated pilot and how can the concept be expanded for other purposes?*

Answering this sub question is approached from a system level perspective and addresses improvements regarding the use of assets, the use of blockchain technology and the current processes related to aFRR. This sub question is answered for both aFRR related processes such as the verification method and for blockchain related improvements.

#### 1.4. Societal and scientific relevance

As mentioned before, unlocking flexibility at the demand side using decentralised assets is considered as an important factor for an effective energy transition [2], [3], [4]. This clearly underlines the societal relevance of the research topic. In addition, the research focusses on new methods for EV owners to participate in grid balancing, which results in (financial) benefit stacking for consumers and market parties.

Regarding the scientific relevance, on a higher level, this thesis contributes to the knowledge on the transition of a centralised vertical system to a decentralised horizontal system. More specifically, it adds new insights in the three considered subjects. The feasibility of deploying EVs for aFRR has been investigated before, but solely based on theory and simulations [13] and never on a practical application and ‘real’ data. Furthermore, the majority of the research on blockchain technology relates to cryptocurrencies [5], whereas research on applications in the electricity sector is scarce. This thesis contributes to this in that respect. In addition, this research proposes a new method for the TSO regarding the verification and settlement phase of aFRR provision. Lastly, apart from the contributions to the individual subjects, the thesis provides new insights in the symbiosis of the three subjects which is depicted in Figure 1.1.

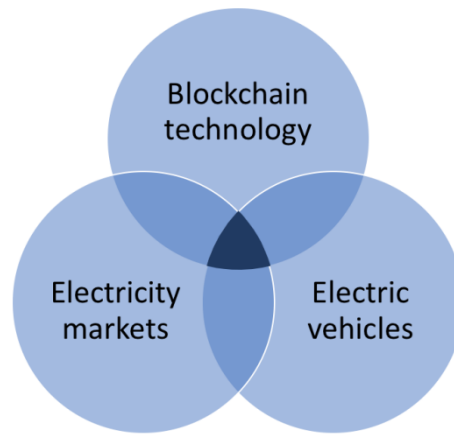


Figure 1.1 Visual representation of the different research aspects and their synthesis where the dark blue part represents the scientific contribution.

### 1.5. Thesis outline

The outline of the continuation of this thesis is depicted in Figure 1.2. In Part I contextual knowledge is constructed regarding electricity markets and blockchain technology. In Part II, the current concept of providing aFRR with EVs is investigated based on the pilot data. Insights from these parts result in the proposed future concepts in Part III in which an aFRR verification method and a blockchain architecture are suggested. The thesis ends with Part IV, in which the implications of the research are determined in the conclusion and discussion.

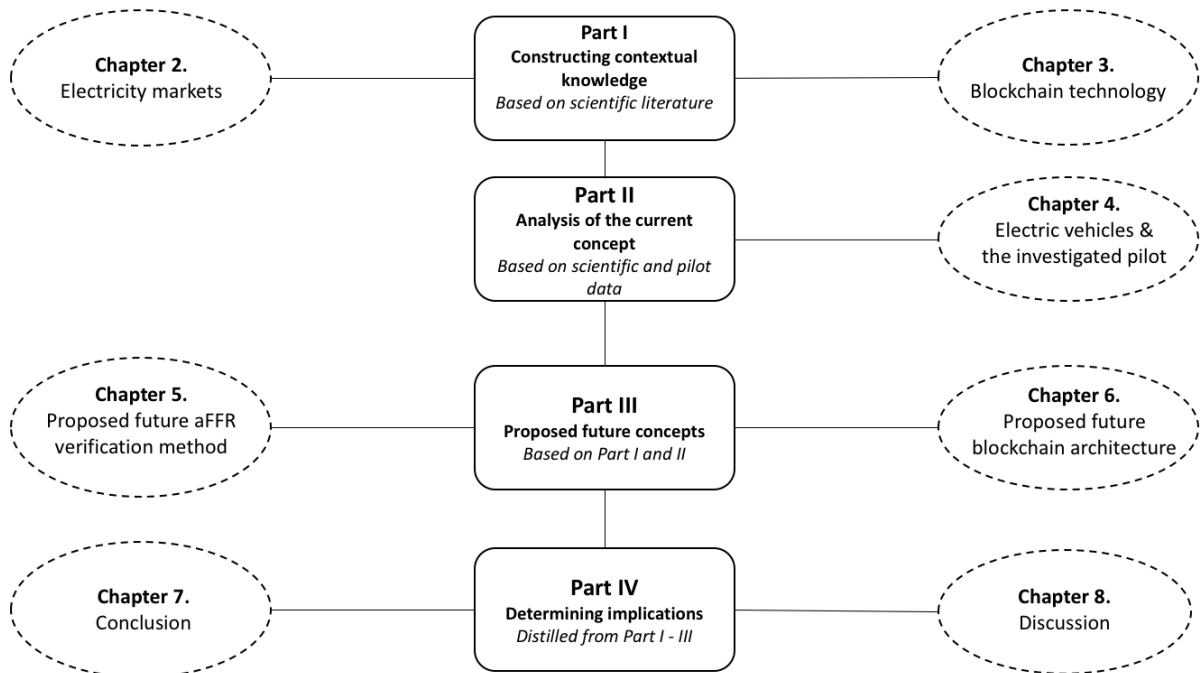


Figure 1.2. Visual representation of the outline of the thesis.

# Part I

Constructing contextual knowledge

## 2. Electricity markets

In this chapter, a short overview of the design and functioning of the electricity markets in the Netherlands is described. The chapter starts with a general overview of the market structure and relevant actors. Hereafter, the functioning of the day-ahead and the ancillary services markets is described, with an emphasis on aFRR. The chapter finishes with an analysis of patterns in activated aFRR volumes and prices.

### 2.1. General market structure

The general structure of the electricity market is determined by different submarkets [14], which include wholesale forward markets, wholesale spot markets and markets for ancillary services. Three phases of activities can be distinguished within electricity markets and power systems operation: (i) The operational planning and scheduling (a priori), (ii) real-time operations and (iii) verification and financial settlement (a posteriori) [15]. Figure 2.1 depicts the chronological order of the different phases. The grey area typifies the focus of this section as future markets and long-term planning are not addressed here.

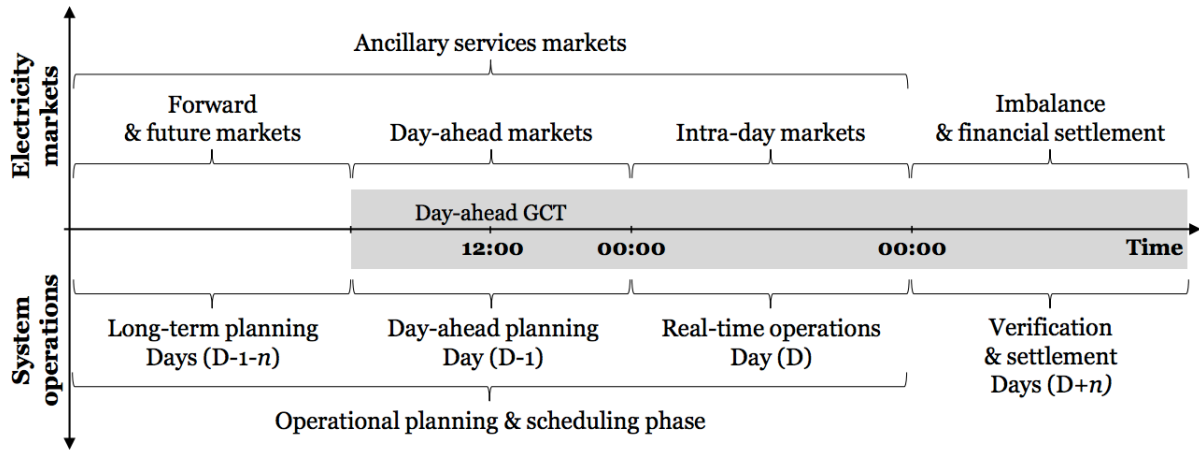


Figure 2.1 Visual representation of the chronological order of the different phases in electricity markets [14].

Section 2.2 elaborates on the day-ahead market, while Table 2.1 gives an overview of different actors whose functions and tasks are relevant for the description of the different phases.

Table 2.1 Overview of main actors and their functions and tasks in the electricity markets.

Actor	Description of functions and tasks
<i>Balance Responsible Party (BRP)</i>	A market participant or its chosen representative responsible for its imbalances [16]. Each BRP is responsible for balancing supply and demand for its portfolio and must inform the TSO about the planned production and demand per ISP of the next day (i.e., E-programmes). Deviations from E-programmes lead to imbalances. In this case, the BRP can either adjust transactions or production/consumption in real time to correct its imbalances. Otherwise the BRP is settled for this imbalance with the imbalance price.
<i>Balancing Service Provider (BSP)</i>	A market participant with reserve-providing units or reserve providing groups able to provide balancing services to the TSO [16]. In the traditional energy system this is done by a small number of BSPs that adjust the power output of centralised conventional power plants. In the future system more BSPs with decentralised and sustainable assets are expected to be deployed.
<i>Energy supplier</i>	The role of the supplier is to source, supply, and invoice energy to its customers. The supplier and its customers agree on commercial terms for the supply and procurement of energy [17]. The supplier must be assigned to the metering points of the customer it supplies [18].
<i>Transmission System Operator (TSO)</i>	According to the electricity act (1998), the TSO in the Netherlands, TenneT, has three obligations: i) building and maintaining the high voltage grid, ii) facilitate efficient and stable electricity markets and iii) balance demand and supply [19].

## 2.2. Day-ahead market

In the Netherlands the day-ahead market is operated by European Power Exchange Netherlands (EPEX NL). All trades on the day-ahead market are made anonymously and thus market parties do not know with whom they trade. All trades are sent to the TSO by both the EPEX and the trading parties [20].

### 2.2.1. Operational planning and scheduling

As stated in Table 2.1, each BRP constructs an E-programme during the day-ahead operational planning, which is sent to the TSO. This E-programme consists of quarterly-hourly time intervals which are called Imbalance Settlement Periods (ISPs). Similarly, the BRP also constructs an energy schedule for the day-ahead market,  $E_{das}(h)$ . Contrary to the E-programmes, the day-ahead market is structured by settlement periods of full hours. For each hour the BRP predicts the net generation and consumption of its complete portfolio. All energy schedules must be submitted before Gate Closure Time (GTC) (i.e., before 12.00 p.m. at the day-ahead). Afterwards EPEX calculates the market clearing price for each hour of the next day by arranging the purchase volumes in a descending order and the sale volumes in an ascending order. The intersection of these supply and demand curves determines the market clearing price. In the case that day-ahead energy schedule,  $E_{das}(h)$  is cleared at market prices it is automatically turned into a day-ahead contract,  $E_{dac}(h)$ , so that  $E_{dac}(h) = E_{das}(h)$  [15]. This results in fully collateralised hourly contracts to which all the BRPs have to comply [20].

### 2.2.2. Real-time operations

During the real-time operations the BRP has to comply to its a priori constructed day-ahead energy contract, so that  $E_{dac}(h) = P_{dac}(h) * \tau_h$  where  $P_{dac}(h)$  is the average power value for the  $h$ th hour and  $\tau_h$  reflects the time interval [15]. Nonetheless, the verification and settlement processes are based on settlement periods of fifteen minutes, which results in a misalignment of time intervals. To deal with this values of  $E_{dac}(h)$  are often simply divided by four which results in  $E_{dac}(l)$ , with  $l = 1, \dots, 96$ . The hourly time intervals on the day-ahead market partly cause the erratic course of aFRR activated volume over the day on which is elaborated in Section 2.3.2.

Any deviations from  $E_{dac}(l)$  result in an energy imbalance position,  $\Delta E(l)$  which can be solved by the BRP within the ISP by adjusting the generation and/or consumption of its portfolio.

### 2.2.3. Verification and financial settlement

This phase, as depicted in Figure 2.1, takes place after the operational day. This applies for both the settlement with the operator of the day-ahead market, i.e., EPEX NL and for the settlement with the TSO. For the verification and settlement phase the energy imbalance is determined according to equation 2.1:

$$\Delta E(l) = E_{dac}(l) - E_{msr}(l) \quad (2.1) [15]$$

In which  $E_{msr}(l)$  expresses the net measured energy volume by metering responsible parties (MRP) during the  $l$ th ISP.

## 2.3. Ancillary services markets

As mentioned before, it is the TSO's responsibility to make sure that imbalances between production and demand of electricity are restored. These imbalances directly influence the frequency of the grid. The nominal frequency of the electricity grid in the Netherlands is 50 Hz. During periods of time in which the power generation is higher than the demand, the frequency increases, while it decreases in case of a larger demand than generation. The boundaries of maximum allowed frequency deviations are determined at 49.8 and 50.2 Hz. To contain and restore the frequency level within the standard frequency range, the injection or withdrawal from the grid should be modified. To establish this, different ancillary services markets exist: Frequency Containment Reserves (FCR), automatic Frequency Restoration Reserves (aFRR) and manual Frequency Restoration Reserves (mFRR)<sup>1</sup>. Figure 2.2 depicts the chronological order and the activation time of the different ancillary services markets.

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<sup>1</sup> Some TSOs also have reserve replacement (RR) capacity, but this does not apply to the Netherlands. Therefore, RR is not discussed in this thesis.

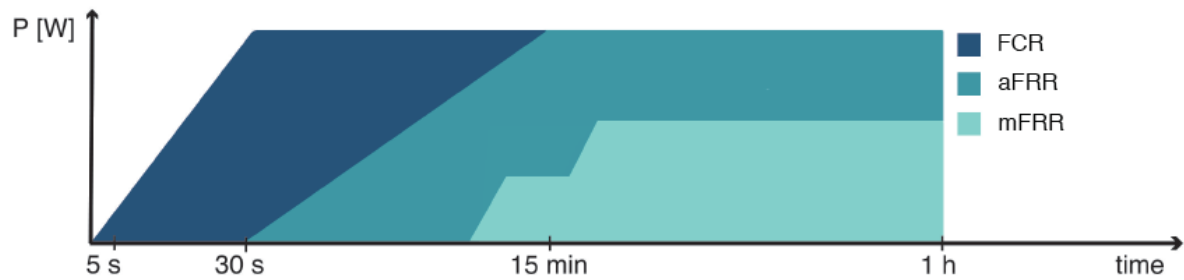


Figure 2.2 A visual representation of the chronological order and activation time of the different ancillary services markets [21].

The activation of FCR should avoid further increase in frequency deviations. FCR is activated automatically in the total synchronous area, which is an electrically connected area with the same frequency. The electricity grid in the Netherlands is part of the synchronous area of Continental Europe, sometimes referred to as the UTCE synchronous area. This area is divided in different Load Frequency Control (LFC) blocks which typically cover one country. Besides FCR, aFRR and mFRR are activated if needed. Contrary to FCR, imbalance in one LFC block does not lead to activation of aFRR and mFRR in all LFC blocks within the synchronous area. This is because aFRR/mFRR is activated within the LFC block of the original imbalance. As the focus in this thesis is about aFRR, FCR and mFRR are not further discussed.

### 2.3.1. automatic Frequency Restoration Reserve

The provision of aFRR can be delivered by two different processes. The minimum required quantity of aFRR is secured through contracts with BSPs. This amounted to 340 MW upward and 340 MW downward aFRR in 2017 and is in accordance with ENTSOE-E CE guidelines [8]. Contracted aFRR must be offered and kept available during all ISPs of the contracted period, which can be monthly and weekly periods. In addition to the contracted aFRR it is possible for (other) parties to provide available aFRR on a voluntary and flexible basis, so called 'non-contracted aFRR' or 'free bids'. These parties can place bids for individual ISPs. Below the planning, real-time operations and settlements phases of aFRR are described.

#### 2.3.1.1. Operational planning and scheduling

Contracted suppliers have to place their bids for up and/or downward control for each ISP of the entire day, ultimately the day before the operational day before 3.00 p.m., which can be updated until GTC. This is currently 2 ISPs (30 minutes) before the ISP of the bid. The total amount of up/downward control must equal the contracted quantity. For other parties a minimum bid size of 1 MW applies. Parties with voluntary bids can submit bids until GTC. Previously, the minimum bid size was 4 MW and the GTC was 4 ISPs (one hour) before the actual ISP. These recent changes increased the opportunities to deliver aFRR with smaller assets of which the future production is more complicated to predict (e.g., EVs or renewable energy production).

The bids of both the contracted suppliers and the voluntary parties are placed on a bid ladder based on price. The contracted aFRR power is not prioritised over voluntary offered regulation power. The offered price is the only determinant for the position on the bid ladder. For the contracted aFRR applies that the maximum price for upward aFRR is the day ahead price + 1000 €/MWh for each ISP and the minimum downward contracted aFRR price

is the day ahead price – 1000 €/MWh with an absolute minimum price of -999,99 €/MWh. Figure 2.3 shows the concept of a bid ladder for upward and downward aFRR.

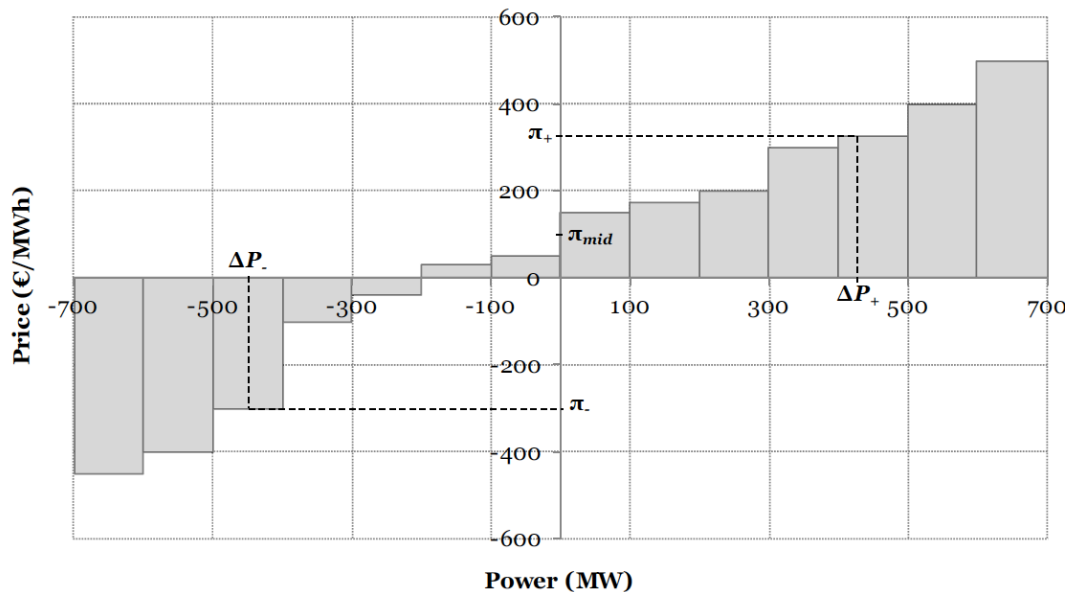


Figure 2.3 Visual representation of a bid ladder example as shown in [14].

The left hand side of Figure 2.3 shows a decreasing order of bids for the provision of downward aFRR. In the Netherlands a marginal pricing system is used. For instance, if a downward balancing capacity,  $\Delta P_-$  (in Figure 2.3 ca. (-)450 MW) is activated, *all* parties with activated bids receive the lowest (i.e., most negative) included bid price,  $\pi_-$  (in Figure 2.3 ca. -300€/MWh). On the right hand side, bids for upward aFRR are shown. These bids are placed in an increasing order. For example, if an upward balancing capacity,  $\Delta P_+$  (in Figure 2.3 ca. 420 MW) is activated, *all* parties with activated bids receive the highest included bid price,  $\pi_+$  (in Figure 2.3 ca. 325€/MWh). The paragraph on the verification and settlement phase elaborates on the financial settlement which is based on the bid ladder.

#### 2.3.1.2. Real-time operations

During the ISP(s) in which aFRR is activated, the TSO sends setpoints to the BSPs with activated bids. These setpoints represent the needed down/upward aFRR provision and are sent in the order of the bid ladder (i.e., from high to low prices for downward activation and from low to high prices for upward activation). The setpoints are indirectly based on the area control error (ACE). The ACE is calculated by equation 2.2 and reflects the system frequency and the imbalance position of a LFC block based on its cross-border power flow.

$$ACE_{NL} = \Delta P_{NL} + \Delta f * \beta_{NL} \quad (2.2)$$

Where  $\Delta P_{NL}$  is the difference between the scheduled and actual cross-border power flows in the Netherlands,  $\Delta f$  is the deviation from the nominal system frequency (i.e., 50 Hz) and  $\beta_{NL}$  (MW/Hz) is the frequency bias constant of the LFC block (in this case the Netherlands). This constant reflects how the system reacts to frequency deviations and can be calculated via equation 2.3:

$$\beta_{NL} = C_{NL} * \beta_{CE} \quad (2.3)$$

Where  $C_{NL}$  is the contribution coefficient of the Netherlands and  $\beta_{CE}$  is the frequency bias constant of the synchronous area Continental Europe. The values of  $\beta_{CE}$  and  $\beta_{NL}$  are updated from time to time to account for control area characteristics [22].

It should be noted that the individual control signals (i.e., setpoints) are not directly derived from the ACE, but on the process area control error (PACE) [15]. As public information on the formulation of the PACE signals is limited, the focus of this thesis is on the resulting signals (i.e., the setpoints) and not on the PACE signals itself.

During ISPs in which aFRR bids are activated, the values of the setpoints are updated on a four seconds interval by the FVR<sup>2</sup>, the automatic system the Dutch TSO uses for power balancing [8]. These parties must be able to show a reaction in their production output to these setpoints within 30 seconds. The minimum ramp up/down rate which is also referred to as the regulation rate must be 7% per minute [8]. Hereby, the total control power is assumed to be delivered after 15 minutes. However, Figure 2.4 shows that this regulation rate is not sufficient for smaller bid sizes.

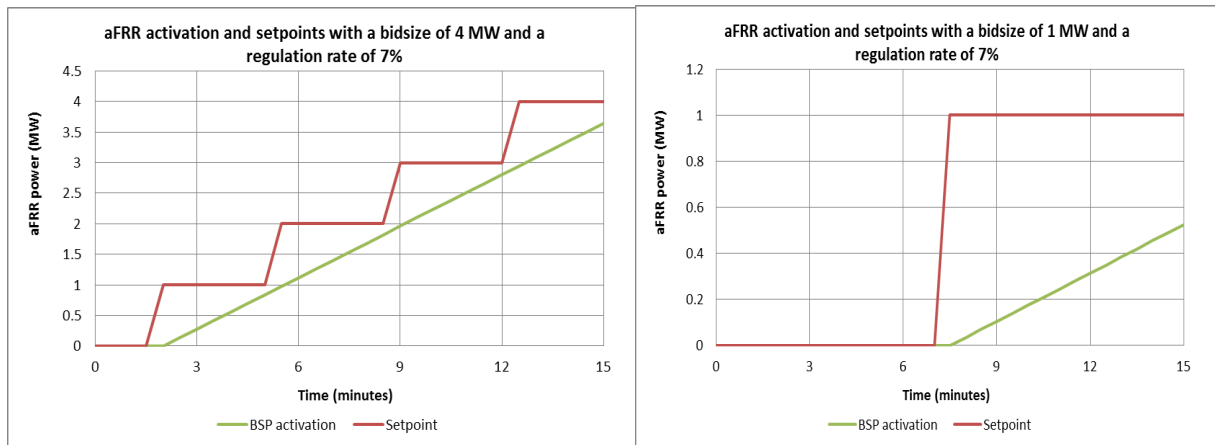


Figure 2.4 Overview of the course of setpoints and bid activation with a regulation rate of 7% for a bid size of 4 MW (left) and a bid size of 1 MW (right).

Figure 2.4 shows that it takes substantial time before the setpoint of 1 MW is sent by the TSO, especially for the 1 MW bid on the right side. This is due to the fact that the rate of sending setpoints also depends on the regulation rate (7% in this case). Moreover, the resolution of sending setpoints is limited to integers (e.g., 0, 1, or 2 etc.). Therefore, the setpoints are rounded to integers (e.g., 0.5 MW is rounded to 1 MW, 1.5 MW to 2 MW etc.). Especially for smaller bids it takes time before 0.5 MW is reached with such a low regulation rate (e.g., this takes 7.5 minutes for a bid size of 1 MW). This leads to the inability to activate full aFRR power within 15 minutes, although the parties do comply with the technical requirements and aFRR product specifications. Therefore, bids with a small bid size (up to 10 MW) should have a higher regulation rate or the resolution in which setpoints can be sent should be improved.

<sup>2</sup> The full terminology in Dutch is: Frequentie Vermogens Regeling

Theoretically, for a bid size of 1 MW a regulation rate of 10% should be the minimum requirement to activate full power within 15 minutes as can be seen below. For EVs, higher regulation rates are possible. In the current pilot the bids have a regulation rate of 21% per minute. Potentially this could be 100% per minute. Figure 2.5 shows the activation for a bid size of 1 MW with a regulation rate of 10% and 21%. The left side shows that 10% is the minimum regulation rate to achieve full power within 15 minutes. The right side shows that with a regulation rate of 21%, full power is already activated in approximately 7.5 minutes.

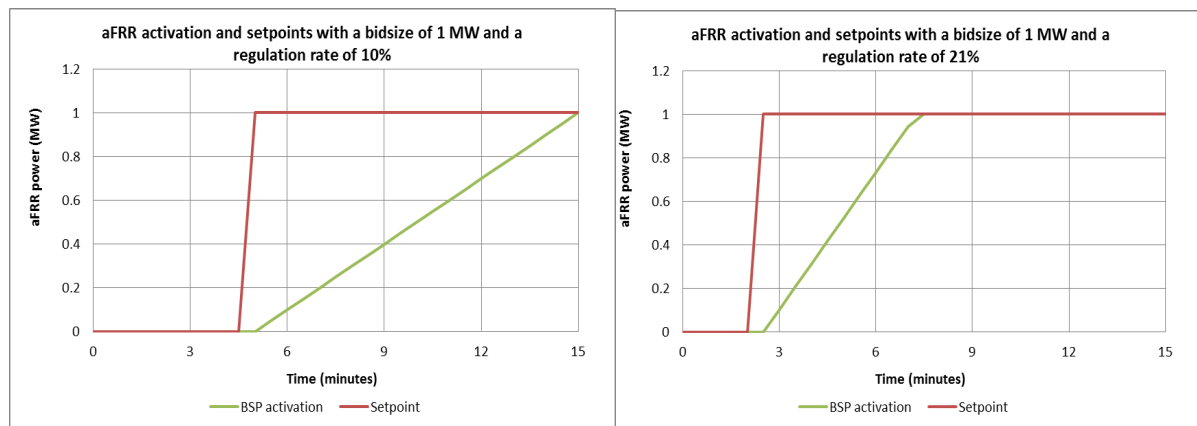


Figure 2.5 Overview of the course of setpoints and bid activation for a bid size of 1 MW with a regulation rate of 10% (left) and 21% (right).

The regulation rate does not only affect the specific ISP in which imbalance has to be restored, but also the ISP afterwards. In the case of a bid size of 1 MW upward aFRR and a regulation rate of 10%, it takes another 15 minutes before the BSP is ramped down (following TenneT's setpoints) to its original net generation. For this ISP the BSP generally receives the aFRR price of that ISP<sup>3</sup>. Also here applies that assets with higher regulation rates would return faster to their original power output.

#### 2.3.1.3. Verification and financial settlement

To verify whether aFRR is delivered correctly, TenneT currently uses reference signals [8]. These reference signals represent the net expected output by each BSP one minute in the future excluding aFRR requested by the TSO. In other words, the difference between the reference signal and actual net output is considered as the quantity of delivered aFRR. The delivered aFRR is currently visually assessed by TenneT's process experts and is rather based on experience and tacit knowledge than on explicit quantified boundaries.

In this verification process, difference aspects are taken into account: i) response delay, ii) inadequate response and iii) the mirroring effect [23]. The mirroring effect relates to the situation in which BSPs do not follow the setpoints correctly and manipulate the reference signal to mislead the TSO to attempt to avoid financial penalties<sup>4</sup>. The reference signal

<sup>3</sup> Only during the absence of a price of the next ISP ('inzetprijs' in Dutch) the price of the previous ISP is used.

<sup>4</sup> This only applies to contracted aFRR suppliers.

should be communicated to TenneT a priori. However, some BSPs do not comply with this rule [23] which offers the opportunity to use the setpoints to calculate the reference signal. Calculating the reference signal by subtracting the setpoints from the actual power output results in seemingly perfect aFRR provision. Figure 2.6 shows of an example of the mirroring effect.

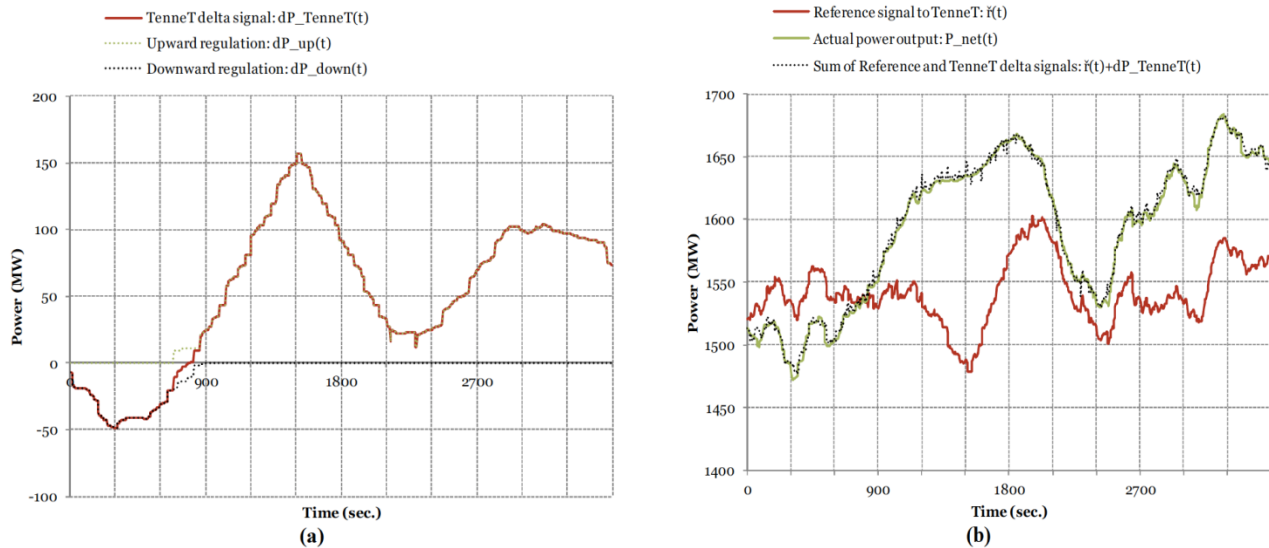


Figure 2.6 A visual representation of the mirroring effect, where (a) shows the delta-signals (i.e., setpoints) sent by the TSO and (b) the reference signal and the power output of the BSP as shown in [23].

Figure 2.6 shows between 900 and 1900 seconds that when the upward setpoints starts to increase the reference signal decreases respectively and when the setpoints decrease the reference signal increases proportionally. In this way, comparing the difference of the actual power output and the reference signal with the setpoints would suggest aFRR is provided as demanded. However, an ex-post analysis showed that the specific BSP manipulated the data by mirroring the reference signal [23].

Another option for TenneT to assess the quality of the reference signal is via physical audits by external independent parties. When aFRR is provided by many decentralised smaller assets it will be more complicated to execute physical audits. This, in combination with the lack of explicit guidelines and automated verification processes, has raised questions within TenneT regarding alternative strategies to verify aFRR provision. In Chapter 5 of this thesis, a new methodology for verifying aFRR provision is proposed utilising the benefits of blockchain technology.

Regarding the financial settlement, a clear distinction should be made between parties (either BSP or BRP) that actively restore imbalances (e.g., by providing aFRR) and parties that passively contribute to the imbalance. For both cases, the financial settlement phase is described below.

#### 2.3.1.4. Financial settlement of active contribution of BSPs

As explained earlier, the verification of aFRR provision is based on the relation of the actual power output, the setpoints sent by the TSO and the reference signal. However, the financial settlement is only based on the setpoints and the marginal price which is represented by equation (2.4).

$$R = \sum \sigma_{up} * p_{aFRR\ up} - \sum \sigma_{down} * p_{aFRR\ down} \quad (2.4)$$

Where  $R$  (€/ISP) represents the revenue per ISP,  $\sum \sigma_{up}$ ,  $\sum \sigma_{down}$  (MWh) equals activated volume and where  $p_{aFRR\ up}$ ,  $p_{aFRR\ down}$  (€/MWh) is the (marginal) imbalance price of the specific ISP. Note that contracted aFRR suppliers also receive a capacity remuneration.

It should be emphasised that the direction of the monetary flows depends on whether it regards upward or downward regulation and whether the imbalance price is positive or negative. This can be summarised by:

*If  $p_{aFRR\ up} > 0$ , then the TSO pays the BSP* (2.5.a)

*If  $p_{aFRR\ up} < 0$ , then the BSP pays the TSO<sup>5</sup>* (2.5.b)

*If  $p_{aFRR\ down} > 0$ , then the BSP pays the TSO* (2.5.c)

*If  $p_{aFRR\ down} < 0$ , then the TSO pays the BSP* (2.5.d)

#### 2.3.1.5. Financial settlement of passive contribution of BRPs

BRPs with an imbalance position, caused by a deviation from their E-programme, are settled with the imbalance price. In the Netherlands the imbalance price for passive contribution is based on the marginal price on the bid ladder for activated aFRR bids. This ensures that the financial consequences of imbalance are paid by the market parties causing the imbalance and that the TSO mainly plays an administrative role.

The monetary flows for passive imbalance depend on the state of the system imbalance. There can be a *shortfall* in the system, caused by lower generation and/or higher demand than expected, resulting in upward aFRR activation [24]. In this case the BRPs with an adverse contribution to the system balance, pay the TSO  $p_{aFRR\ up}$ . BRPs with a (passive) beneficial contribution to the system balance, receive  $p_{aFRR\ up}$ .

Similarly, there can be a *surplus* in the system, caused by higher generation and/or lower demand than expected, resulting in downward aFRR activation [24]. In this case the BRPs with a beneficial contribution to the system balance pay the TSO  $p_{aFRR\ down}$ . This could sound counterintuitive, but as  $p_{aFRR\ down}$  is usually lower than the day-ahead price it results in a financial benefit. The TSO pays then  $p_{aFRR\ down}$  to the BRPs with an adverse contribution to the system balance, which is a lower price than the BRPs would have received on the day-ahead market resulting in a financial penalty. Note that if  $p_{aFRR\ down}$  is negative, similarly as in (2.5.d) the monetary flows are exactly opposite which results in higher financial benefits and penalties

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<sup>5</sup> In practice, this never happens.

### 2.3.2. Patterns in activated aFRR volumes and prices

In this section the activated aFRR volume and the price delta between aFRR and the day-ahead prices during the last years are analysed. In Part II, these trends are compared with trends in the charging behaviour of EVs to identify any potential (mis)matches. As the EVs can currently only provide upward aFRR, this section also focusses on the trends in upward aFRR volumes and prices.

As BRPs are active on the day-ahead market, the financial incentives to provide aFRR depend on the difference between the aFRR price and the day-ahead price (i.e., the price delta) per ISP. Figure 2.7.a shows the average price delta for activated upward aFRR over the last years for each ISP on a weekday and on a weekend day and Figure 2.7.b shows the average activated aFRR volume. As the values reflect ISPs in which aFRR is activated, ISPs without activation (i.e., price and volume equal 0) are not included in the analyses.

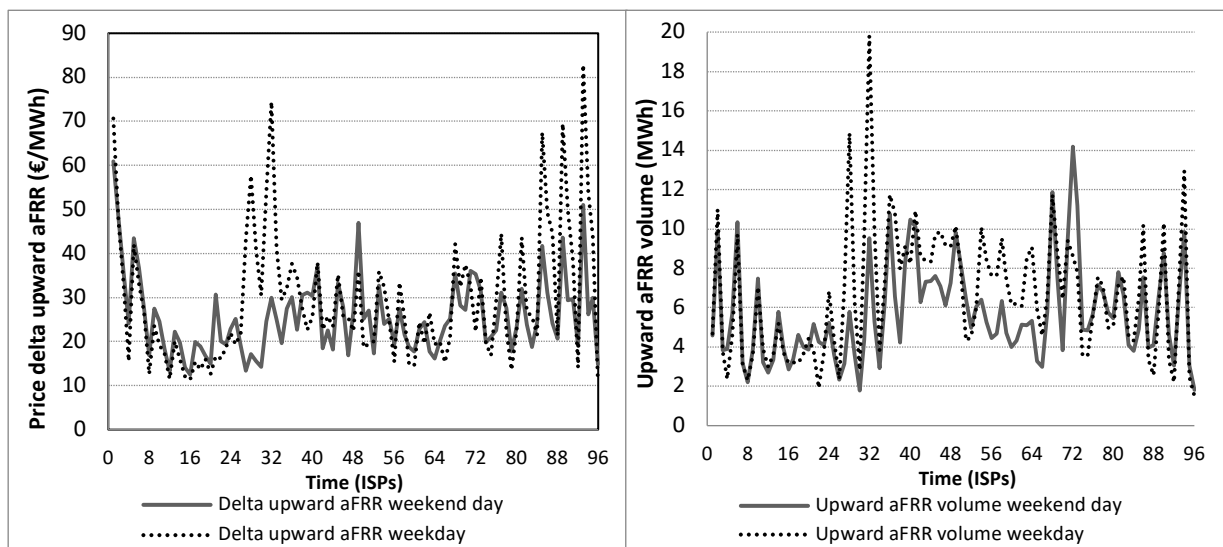


Figure 2.7 Visual representation of aFRR data. The average price delta per ISP 2014-2017 (a). The average activated volume per ISP 2014-2017 (b).

Figure 2.7.a and Figure 2.7.b show multiple similarities. Both the price delta and volume are generally higher on a weekday than on a weekend day. Both graphs show peaks in the morning (mainly around ISP 27-32) and in the evening (mainly around 85- 93). During these ISPs in the morning demand quickly increases, but the low ramp-up rate of conventional power plants lead to a lag in the increase of production which results in higher imbalance volumes and prices. Similarly, during the ISPs in the evening the ramp-down rate of the conventional power plants is too low to keep up with sharp decrease in demand.

Lastly, perhaps the most notable similarity is the erratic pattern of the graphs. This can be explained by the fact that the international day ahead market is based on time intervals of 60 minutes, whereas the E-programmes and aFRR are based on time intervals of 15 minutes. The high volume international trading on the day ahead market strongly affects the activated aFRR volumes and prices. This is caused by suppliers which have to ramp up/down their production when a new time interval on the day ahead market starts. Again, due to the low ramp up/down rate of conventional power plants that still represent a large

share of most BRPs' portfolio, suppliers often have to start ramping up/down during the fourth ISP of the hour and continue in the first ISP of the next hour. These periods of ramping up/down generally lead to a larger imbalance and hence to a higher activated aFRR volume and higher price deltas. The Clean Energy Package dictates that in 2025 the time intervals of all electricity markets should equal the time intervals of the ISPs. This would lead to smaller and thus more gradual steps in net generation on the day-ahead market, which could also lead to a less erratic course of activated aFRR volume and prices. Additionally, restoring imbalance with assets with higher regulation rates, such as EVs, could also result in a less erratic pattern of imbalance volumes and prices, because imbalances could be restored faster.

## 2.4. Summary

In this chapter, the actors and the functioning of electricity markets that are relevant for the investigated topic are described. In particular, the different phases of aFRR provision (i.e., planning and scheduling, real-time operations and verification and settlement) in the current system are explained.

For the real-time operational day, it is shown that the minimum required regulation rate of 7% per minute is insufficient to reach full aFRR activation within 15 minutes for bids up to 10 MW. This could be solved by increasing the required regulation rate for smaller bid sizes (e.g., for a bid size of 1 MW a minimum regulation rate of 10% is sufficient). The issue could also be solved by increasing the resolution of sending setpoints. Currently the TSO only sends integers. Changing this into decimals results in faster activations. For the verification and settlement phase, it is described how market parties can deceive the TSO by manipulating the reference signal [23].

The chapter also contains analyses of patterns in activated aFRR prices and volumes over the last years per ISP. These analyses show a varying and erratic course over the day. This can be explained by the time intervals of one hour on the day ahead market, which results in relatively large changes in production. This is accompanied by larger imbalances due to the low ramp-up/down rate of conventional power plants. The information in this chapter is presented to construct contextual knowledge and is used in the next chapters to assess how EVs and blockchain technology could be incorporated in the current system.

### 3. Blockchain technology

This chapter starts with briefly explaining the most important mechanisms that shape the foundations and opportunities of blockchain technology. Hereafter different types of blockchain technology, associated advantages and some energy related blockchain initiatives are described. The chapter finishes with a description of the blockchain application in the investigated pilot.

#### 3.1. Blockchain in a nutshell

A blockchain is a distributed ledger technology (DLT) than can record transactions between different parties in a transparent, verifiable and permanent way [12]. The goal of blockchain technology is creating a decentralised environment in which no third party or central authority is solely in control of transactions and data [5]. Currently different types of blockchain exist, but the technology was introduced for the first time in 2008, by the yet mysterious identity of Satoshi Nakamoto, as enabler of a peer-to-peer electronic cash system, better known as Bitcoin [25]. This proposed payment system is based on cryptographic proof rather than relying on a trusted third party such as a bank. This leads to the opportunity for two parties, who do not necessarily trust each other, to transact directly in a trustworthy way which is sometimes referred to as *trustless trust*.

##### 3.1.1. Encryption of transactions

To secure transactions on a blockchain application such as Bitcoin, asymmetric encryption is used. For asymmetric encryption, contrary to symmetric encryption, a different key is needed to encrypt a transaction than to decrypt it. Each user possesses a public and a private key to encrypt and decrypt transactions. The two keys form a key-pair which are linked, but are not mathematically derivable from each other. Consider an example, in which Alice wants to send a transaction to Bob. Alice uses Bob's public key to encrypt the transaction. The transaction can now only be decrypted by Bob's private key that is only known by Bob himself. Alice additionally encrypts or signs the transaction with her private key. At a first glance this might seem useless as everybody can decrypt this using her public key. However, Alice is the only one who can encrypt this transaction with her private key, which guarantees that she was the sender. Ergo, by encrypting the transaction with Alice's private key and Bob's public key, Bob is the only one who can fully decrypt the transaction, but it is publicly known who the sender and receiver are. A timestamp is added to the transaction to avoid double spending [25].

##### 3.1.2. Blocks and hashes

The transactional information on a blockchain is stored in blocks. Each block is identifiable by its cryptographic hash and each block's hash references the hash of the previous block which leads all the way back to the genesis block. This results in a chain of blocks, hence the "blockchain" naming [26]. A hash function uses a string of arbitrary and variable length as input and leads to an output string with a fixed length [27]. Hashes have a one-way character and are used as a unique digital fingerprint. An input string of variable and arbitrary length is easily computed into an output string with a fixed length of 40 characters [28]. Contrary, when only the output string is known, it is practically impossible to calculate the input string. In proper hash functions no correlation between the input and output

string can be derived. More specifically, even if one character is changed in the input string, the output string (i.e., the hash) can be completely different.

In Bitcoin, the best-known application of blockchain, each block in the chain contains transactions. These transactions, in Figure 3.1 referred to as Tx0, Tx1, Tx2 and Tx3, are individually hashed. These hashes are hashed again and again in combination with other hashes all the way up to the root hash (i.e., Tx\_Root in Figure 3.1) in the block header. This structure is also known as the Merkle tree. Each block header also contains the hash of the previous block header. Saving the hash of the previous block header results in data immutability, because manipulating the data (i.e., transactions or timestamp) in a block would lead to a different hash and thus to inconsistencies in the chain. By only saving hashes the required storage capacity of the blockchain is reduced. The block header also contains a nonce, which is an arbitrary integer that indicates the difficulty to solve the mathematical puzzle necessary to create a new block. Blocks can be added to the chain in various ways. This is further discussed in Section 3.2.

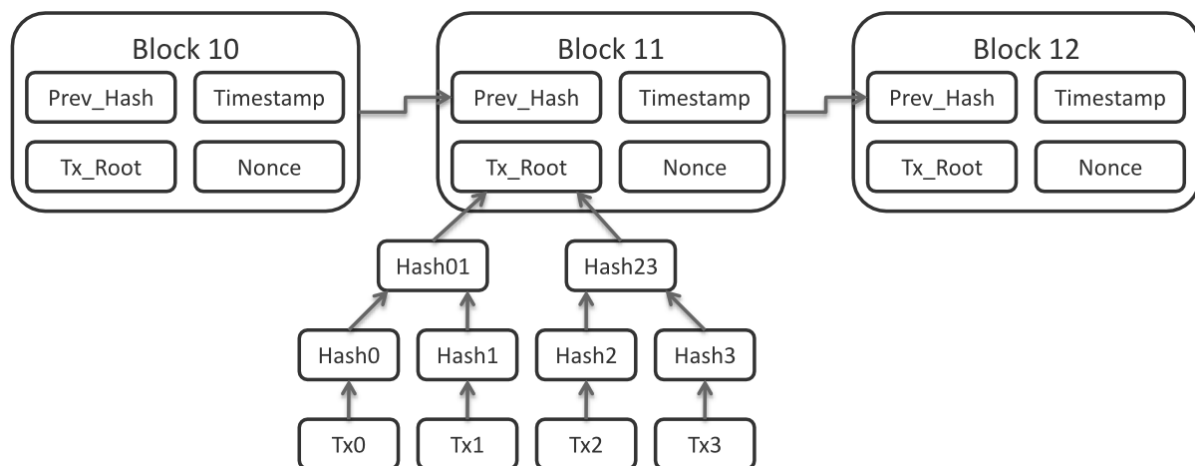


Figure 3.1 The partial structure of blocks and block headers [29].

### 3.2. Consensus models

Different protocols exist on how consensus is reached regarding how and by whom blocks are added to the blockchain. The most popular protocols, Proof of Work (PoW), Proof of Stake (PoS) and Practical Byzantine Fault Tolerance (PBFT) are described below.

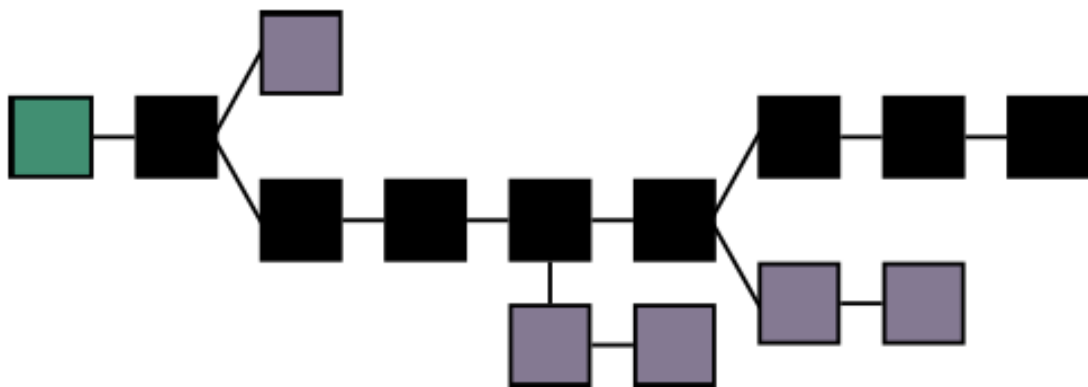
#### 3.2.1. Proof of Work

As described above, the hashes of all transactions, following the Merkle tree structure, are referenced in the root hash. In a PoW protocol, the first node in the network that finds the right inverse of this hash is allowed to add a new block to the chain, which is often referred to as mining. As mentioned in Section 3.1.2, the inverse of the hash is not mathematically derivable and can only be found by many random attempts. The essential idea and assumption behind this mechanism is that none of the nodes in the network possesses enough resources to be able to achieve the majority of the computational power. Hence the power of adding new blocks to the chain is distributed over the network, excluding the

possibility that one participant in the network can manipulate data on the blockchain for its own benefits.

In the Bitcoin protocol, it is stated that roughly every ten minutes a new block is added [30]. As the computer power of the network generally increases over time, the difficulty of finding the inverse hash is changed every two weeks to roughly maintain the rate of 6 blocks per hour. This difficulty is reflected by the nonce, which is an integer of which the probability of repeating a previously generated value is insignificant. The higher the nonce, the lower the probability the inverse hash is found, currently resulting in quadrillions ( $10^{15}$ ) of hashes [30]. This PoW protocol causes the exorbitant electricity use of the Bitcoin blockchain, which is estimated, at the time of writing, at approximately 60 TWh/year. This is comparable to the entire yearly electricity use of countries like Colombia and Switzerland [31] [29]. The same source estimates that one Bitcoin transaction equals the amount of electricity needed to power a U.S. household for approximately 32 days. Another disadvantage of the Bitcoin blockchain is the transaction rate, which is rather low compared to mainstream transaction processors such as Visa credit card (i.e., seven Bitcoin transactions per second vs. 2000 Visa transactions per second) [32]. Lastly, PoW models are based on the assumption that no node(s) can achieve a majority of the computational power. However, the protocol is vulnerable to the so called '51% attacks'. During such attacks, large miner pools can cooperate to reach a minimum 51% of the computing power. If the attackers succeed, then they can manipulate the validation of transactions and the creation of new blocks for their own benefits.

It sometimes occurs that different parties/miners simultaneously find the solution of the next block's hash. This leads to the generation of two new blocks at the same time. This is often referred to as a split or fork, which results in two different truths. The block on which the most later generated blocks are chained to, is considered as the 'real' truth, because the chain with the most cumulative Proof of Work (i.e., the longest chain) is considered as the valid chain by the network [25]. Figure 3.2 shows an overview of a blockchain in which the green block represents the genesis block, the grey blocks represent blocks which are not included after a split, sometimes referred to as orphan blocks [26] and the black blocks represent the longest and thus the valid chain.



*Figure 3.2 A representation of the genesis block, orphan blocks and the valid chain [33].*

### 3.2.2. Proof of Stake

Another consensus model that is becoming increasingly popular is the Proof of Stake (PoS) protocol. An example of a PoS protocols is Ethereum's algorithm called Casper [34]. In a PoS protocol there are no miners that generate blocks, but validators. The probability that a validator is chosen to create a block is proportional to the validator's stake of the block. So instead of miners that invest in computational power in a PoW model, validators financially invest to obtain stakes in the block in a PoS protocol. Validators do not receive rewards for generating a new block (as in the case of Bitcoin), but they do receive the transaction fees of all transactions in 'their' blocks. These transaction fees are paid by users in return for the validation of their transactions. The idea is that validators are incentivised to correctly fulfil their verification tasks, because of the rewards (i.e., transaction fees) they obtain.

However, naïve PoS algorithms suffer the so called 'Nothing at Stake' problem. In a PoS protocol, contrary to a PoW protocol, negligible resources (e.g., computer power) are needed to create the next block. Therefore, validators can 'vote' for more than one block after a fork since there is 'nothing at stake'. Voting for multiple blocks increases the probability of being the validator of the next block. This boosts the revenues through more transaction fees. This would result in multiple branches of the chain which facilitates double spending by malicious attackers. In [35] a mechanism is proposed to prevent this. An advantage of a PoS protocol is the eliminated need to randomly calculate quadrillions of hashes, which lowers the electricity consumption drastically. In addition, advantages lie in the invulnerability regarding 51% attacks.

### 3.2.3. Practical Byzantine Fault Tolerance

The Practical Byzantine Fault Tolerance (PBFT) protocol, already proposed in 1999 in [36], was the first state-machine replication algorithm able to tolerate Byzantine faults. The most famous example is the Byzantine Generals Problem already introduced in 1982 [37]. In this example, multiple generals (e.g., 9), who are physically separated, have to vote whether to attack or retreat via messages. If four of them vote 'attack' and four of them vote 'retreat' a ninth general could corrupt the voting process by messaging 'attack' to the generals that voted 'attack' and messaging 'retreat' to those who voted likewise. In this case, only four generals attack, resulting in an unfavourable outcome.

To add a transaction on the blockchain using a PBFT consensus algorithm, a transaction request, the so called 'primary replica' [36], is sent to the nodes in the network. The validation process is basically a voting process in which the votes of different nodes are replicated and shared amongst the other nodes multiple times to detect any voting inconsistencies as described in the Byzantine Generals Problem. A 2/3 voting majority is required to achieve consensus [38] and thus to add a transaction on the blockchain.

In order to ensure reliable results, the number of replicas should minimally equal  $3f + 1$ , where  $f$  represents the number of faulty nodes in the system [36]. Therefore, the PBFT consensus is mainly suitable for blockchain networks in which the different nodes are known and identified. Section 3.3 elaborates on different types of blockchain technology. Similarly, but slightly different is the more recently proposed Cross-Fault Tolerance (CFT) algorithm, which is a more simplified and efficient version of the PBFT model [39].

These protocols are proposed as efficient mechanisms for a low number of nodes in the network, but the messaging overhead increases significantly as the number of nodes increase [35]. Therefore, the PBFT and CFT protocols are in particular interesting for blockchain solutions with few nodes such as permissioned and private blockchains, whereas the PoW and PoS protocols are merely suitable for public and permissionless blockchains. The differences between these different types are described in the next section.

### 3.3. Public vs. private and permissionless vs. permissioned blockchain

A clear distinction can be made between a public and a private blockchain. In a public blockchain any participant can join the blockchain, has full data access and can add transactions. In a private blockchain only a predetermined set of users is granted (full) access to the blockchain. Regarding the consensus mechanisms, permissionless and permissioned blockchains can be distinguished. In a permissionless blockchain, each user can participate on the blockchain without restrictions. In a permissioned blockchain, users are restricted in their rights regarding the actions they can perform on the blockchain (e.g., reading and writing). Figure 3.3 gives an overview of the different types of blockchain.

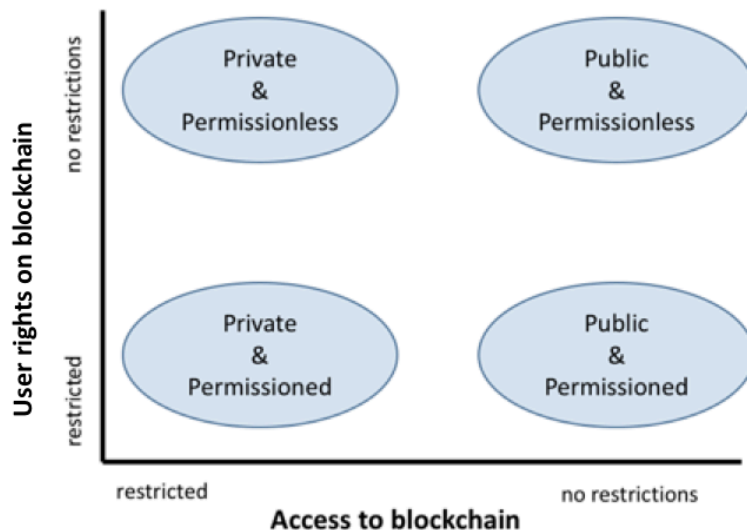


Figure 3.3 An overview of the characteristics of different types of blockchain.

A public and permissionless blockchain is the purest form of a blockchain as it results in access and transparency to all participants and the power of new block creation is theoretically fully decentralised. However, a permissioned blockchain offers advantages such as higher transaction rates, lower transactions costs and a lower electricity use [40]. This can be explained by the used consensus mechanisms, which have a more lightweight character regarding computational power. Besides the number of nodes in the network is in general simply lower, which requires less validation in order to reach consensus in the network. Note that a public and permissioned blockchain is theoretically possible, but no practical applications seem to be developed yet.

### 3.4. Smart contracts

Smart contracts provide interesting opportunities for applications with blockchain technology. Smart contracts were, already in 1994 by Nick Szabo, defined as ‘computerised

transaction protocols that execute the terms of a contract' [41]. Smart contracts are based on 'if-then logic'. This logic guarantees that a predefined set of input values or conditions leads to predefined output values or actions. In traditional contracts, mutual trust is still needed for the execution of transactions. This does not apply to smart contracts, as the contracts are defined and executed automatically by codes [42]. In this way, smart contracts can dramatically increase the efficiency of administrative processes and can radically redefine how transactions between parties can be set up and automated [43]. The combination of blockchain technology and smart contracts can be used for many different applications varying from monetary transactions to automated logging and executing of processes in large and distributed supply chains.

### 3.5. Directed Acyclic Graphs: the successor of blockchain technology?

In 2017, a new kind of distributed ledger technology was introduced which is proposed as the evolutionary succeeding of blockchain technology [44], named the tangle. This new technology can be categorised as a Directed Acyclic Graph (DAG). The tangle is a distributed ledger technology, because the verification of the transactions and updating of the ledgers happens at a decentralised level. However, information is not stored in blocks, but on the tangle itself. Furthermore, there is no difference between (regular) participants and miners as every participant is involved in the verification process. This distinguishes the tangle fundamentally from blockchain technology.

The most developed application of the tangle is the cryptocurrency IOTA. The name refers to both Internet of Things (IoT) and *iota*, the smallest letter of the Greek alphabet. This name is chosen rather adequately as the application is meant to enable micro machine-to-machine

(M2M) transactions in the IoT industry. Figure 3.4 shows a visual representation of the tangle.

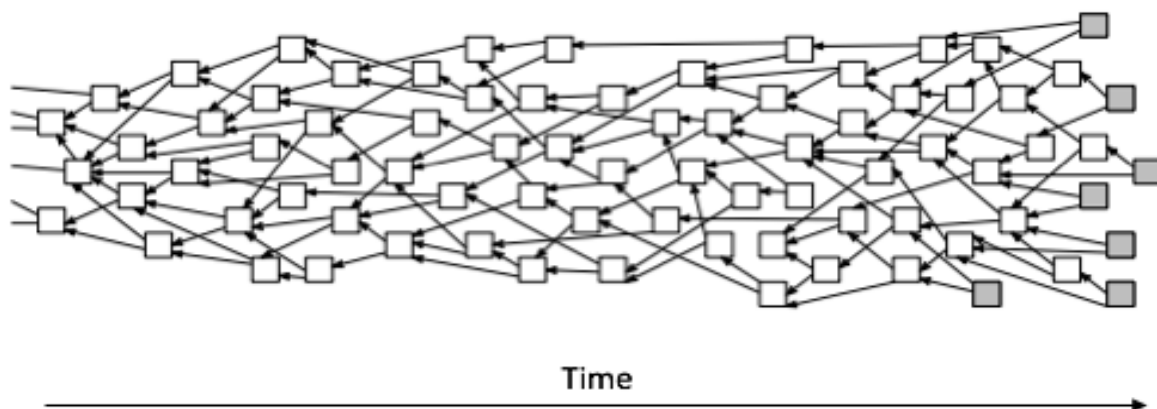


Figure 3.4 Visual representation of the structure of a tangle. Adapted from [44].

Each square represents a transaction. The white squares are verified transactions whereas the grey ones are (yet) unverified transactions. Each participant who wants to add a transaction to the tangle, has to approve first two earlier transactions. This is done by checking whether the previous transactions are not conflicting by facilitating (rather negligible) PoW (i.e., computing power). It should be noted fact that this required PoW is rather low, is said to be to result in higher security risks [45]. If a participant has validated

two transactions, its square (i.e., transaction) is added to the tangle after which it has to be validated by two transactions which are added later on.

The tangle does have two major advantages compared to blockchain technology. The first advantage is that transactions are feeless. In blockchain applications; such as Bitcoin and Ethereum, miners have to be paid to validate transactions. These fees can be rather high (e.g., in December 2017 Bitcoin transaction fees spiked up to over 50 USD [46]). These fees are, especially for micro M2M transactions, too high for an efficient payment system. The second advantage is that whereas a blockchain becomes slower (i.e., lower transaction speed) with a higher number of transactions, the tangle becomes faster. In case of the tangle, an increase in transactions means that participants can faster find two previous transactions to verify, which makes it a technology that is well-scalable.

However, this scalability is not only a strength, but also a weakness of the tangle. In case of a low number of transactions, the transaction speed will be low. In [44], a method to solve this problem is proposed by adding empty transactions to increase the probability that transactions are validated. However, sending empty transactions (which have to be verified themselves) to verify other transactions faster does not seem to be a very efficient solution. Hence, the tangle will only be effective in case of many and frequent transactions. This does not eliminate the potential for EVs related applications, taking into account the expected high increase of EVs in the next ten to fifteen years.

### 3.6. Advantages of blockchain

Blockchain, or distributed ledger technology in general, offers various advantages of which a selection is shown in Table 3.1. The two advantages in bold are unique for blockchain whereas the others are not blockchain specific.

*Table 3.1 General advantages of blockchain technology*

Advantages of blockchain
<b>Decentralised control (no central/third party or middle man needed)</b>
<b>Trustworthy transactions between parties without trust (trustless trust)</b>
Data immutability (non-repudiation of transactions)
Transparency
Traceability
Lower risk of attacks (no single point of failure)
Automation possibilities (smart contracts)
High availability
No duplication possibilities (double spending)

### 3.7. Blockchain initiatives in energy sector

The potential advantages of blockchain technology are recognised by various organisations in the energy sector. This has resulted in many initiatives and applications some of which are listed in Table 3.2. In some applications, blockchain is used as enabler of transactions in a decentralised energy system between parties that do not necessarily trust each other (e.g., peer to peer trading). In other applications, such as in long and complex supply chains,

the key reason to use blockchain is more related to the traceability of origin which is established by adding a digital fingerprint via the earlier described hashing mechanism.

*Table 3.2 Examples of energy related blockchain applications.*

Application	Description
<b>Brooklyn Microgrid</b>	Independent microgrid in Brooklyn, New York, with peer-to-peer trading via a virtual blockchain community energy market platform, based on Ethereum [6].
<b>De Ceuvel/Jouliette</b>	Small Dutch community in which residents can trade PV energy with tokens (Jouliettes) on a blockchain platform. [47]
<b>Bankymoon Usizo</b>	Energy and water meters in African schools are connected to a Bitcoin based blockchain. From all over the world, donations lead directly to funds which can be spent by the school on energy and water. [48]
<b>GrünstromJetons</b>	Customers in Germany receive tokens via smart contracts. When consuming during moments of high availability of green electricity, consumer receive green tokens. During low availability the tokens are grey. [49]
<b>Powerledger</b>	An Ethereum based peer-to-peer energy trading platform in Australia. Experiments will soon be held in the Japanese market as well. [50]
<b>WePower</b>	An Ethereum based platform on which developers can sell renewable energy upfront to raise capital. Started in Estonia, but expanding throughout Europe. [51]

### 3.8. Blockchain in the investigated aFRR pilot

In the current pilot project in which EVs are charged smartly to provide aFRR, a blockchain solution is used as well. The used blockchain technology is a Hyperledger Fabric. The Hyperledger Fabric is one of the best-known (private) permissioned platforms and is designed for consortiums in which the identities of the participants are known, registered and verified [35]. The Hyperledger Fabric is developed by the Linux Foundation in which many large corporates such as IBM and Microsoft are participating. It can support multiple consensus mechanisms, but due to the above-mentioned character of the Hyperledger Fabric, a relatively lightweight consensus model such as a PBFT or CFT protocol would be most suitable. A Hyperledger Fabric offers the possibility to integrate smart contracts in their logic layer called chain code. The Hyperledger Fabric comes with some general ‘if-then logic’ in order to encode and encapsulate the rules and processes that govern transactions [52]. However, no pilot specific smart contracts are used (yet).

There are several reasons why blockchain might have relevance for the TSO regarding aFRR provision in the future. In the current situation, aFRR is provided by only a couple of BSPs through large centralised assets and data is transferred via leased lines. Using leased lines in the future with the potential deployment of multiple BSPs and thousands of decentralised assets is technically and financially infeasible. The distributed character of blockchain technology could provide a solution for the scalability issue and match the potential decentralised landscape of aFRR provision in the future.

Another potential advantage of blockchain technology relates to the processes in which is verified whether aFRR is actually provided as demanded by the TSO. Blockchain could

increase the transparency and the automation via smart contracts with respect to the verification. In this way, the burden on the TSO regarding the verification processes can be reduced. In Section 6.1, this is discussed more extensively.

Figure 3.5 shows two systems. Figure 3.5.a shows a centralised system in which all BSPs send their data to the TSO, that manages a central database. This represents the current situation. The TSO is the centralised party that updates the database based on the data it receives from the BSPs. Figure 3.5.b shows a potential future system with a larger variation of aFRR providing assets such as EVs, home batteries and perhaps still one or multiple conventional power plant(s). This results in a more decentralised character enabled by the blockchain technology. The ledger is updated by all participants in a decentralised way.

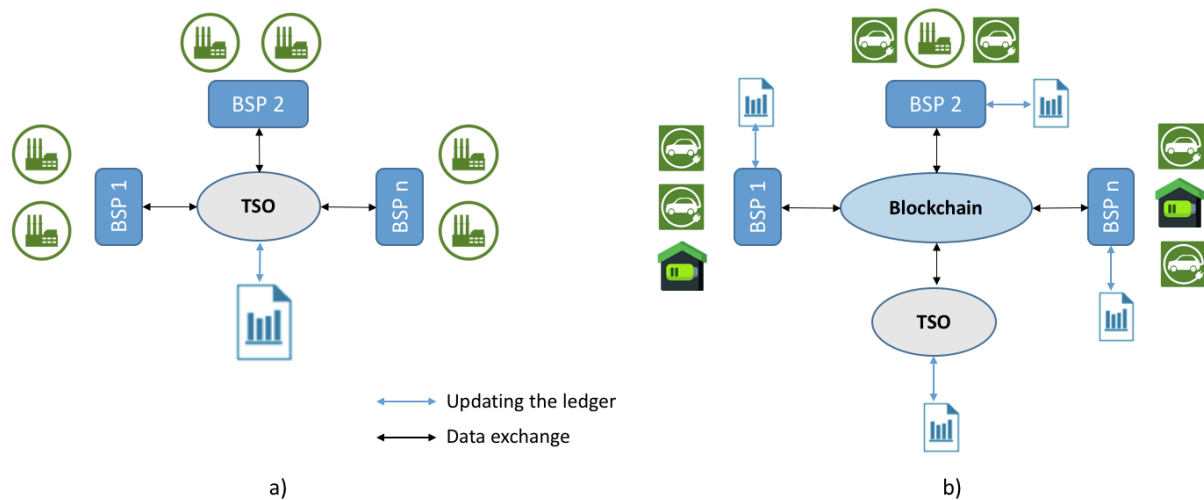


Figure 3.5 Representation of a centralised system (a) and a decentralised system using blockchain technology (b), where 'n' represents the number of BSPs in the system.

### 3.9. Summary

In this chapter, the general functioning, advantages and disadvantages of blockchain technologies are explained. Relevant advantages for the investigated application relate to data immutability, transparency and efficient automation of administrative processes via smart contracts. The chapter also touches upon IOTA, a DLT that is proposed as the successor of blockchain technology and specifically developed for IoT applications and M2M payments. This DLT differs from blockchain technology since data is stored in a tangle instead of blocks, there are no miners and the consensus model is dissimilar. Compared to blockchain technology, the feeless transaction and the scalability (e.g., transaction rate increases with a higher number of transactions) are the main advantages of IOTA, however security issues are expected to be higher than in other technologies.

Furthermore, this chapter describes some energy related blockchain applications and concludes with an introduction on how and why blockchain technology is used in the investigated pilot. This is further elaborated in Part II, where a more detailed overview of the pilot processes is presented according to the same structure as the description of the aFRR phases in Chapter 2.

The information in this chapter is presented to construct contextual knowledge regarding blockchain technology, which is partly used to answer sub question 2: *What is the added value of blockchain technology for the utilisation of EVs for aFRR?*. Besides, constructing the contextual knowledge regarding blockchain technology is used for the designing of the architecture of the proposed future concept in Part III.

## Part II

Analysis of the current concept

## 4. Electric Vehicles and the investigated pilot

In the traditional energy system aFRR is provided by large centralised production assets such as gas fired power plants. TenneT foresees a larger role for decentralised assets (e.g., EVs) deployed for grid balancing in the future. In this chapter the deployment of EVs for aFRR provision is described based on the investigated pilot project (which is called ‘the pilot’ from now onwards) with Vandebron carrying the BSP role.

Firstly, the technical characteristics of EVs are described including the charging rate, energy consumption, charging profiles and how this relates to the required fleet size. Secondly, the processes in the different phases of aFRR provision (i.e., planning, real-time operations and settlement) in the pilot are assessed. Thirdly, the data exchange via the blockchain is described with respect to level of resolution and frequency. Lastly data analyses show the performance regarding the aFRR provision and the chapter finishes with suggested improvements.

### 4.1. Energy consumption

In the pilot, EVs are used to provide aFRR by postponing residential charging processes. In this way, demand is decreased which is equivalent to upward aFRR provision. In the future downward aFRR could be enabled by increasing the charging rate, increasing the number of charging EVs or by providing vehicle to grid (V2G) services. However, in the pilot this option is not yet enabled.

At this moment, Vandebron only uses Tesla vehicles to deliver aFRR. The charging behaviour of the EVs is regulated through the Tesla application by the Vandebron. Tesla EVs usually have a maximum residential charging rate of 11 kW [53]. If all EVs would charge on a maximum power rate, then 91 EVs charging in the same ISP would be required to reach the bid size threshold of 1 MW<sup>6</sup>. However, it is rather improbable that all assets (i.e., the complete fleet) charge simultaneously. In Section 4.2 a more extensive analysis of the needed number of EVs per MW is contemplated taking existing charging behaviour into account.

In [13] an average driving distance of 43 km for Tesla EV drivers in the Netherlands is assumed. With the average energy consumption of 0.200 kWh/km and two trips per day, this leads to an energy consumption of 17.2 kWh/day. With a charging capacity of 11 kW this would lead to a charging time of approximately 1.5 hours per EV per day. However, the last part of the charging cycle is at a lower charging rate. In the pilot, EVs that reach a state of charge (SoC) higher than 85% are excluded from the aFRR pool, because of decreasing and possibly more unstable charging rates during the last stage of the charging process. This can be explained by the fact that Li-ion batteries are charged through two different steps. If the battery is relatively empty it is charged at constant current until its voltage reaches a predetermined limit. Hereafter, the battery is charged at constant voltage while the current decreases. This method is referred to as constant current-constant voltage (CC-CV) charging [54].

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<sup>6</sup> Note that other brands usually have a lower maximum charging rate. This results in a higher number of EVs required to reach the threshold of 1 MW.

The amount of energy available for aFRR provision per EV per day can be calculated by using equation 4.1.

$$E_{flex} = EC_{needed} - \left(1 - \frac{SoC_{barrier}}{100\%}\right) * E_{battery} \quad (4.1)$$

Where  $E_{flex}$  [kWh] equals the amount of energy that can be shifted in a flexible way to provide aFRR,  $EC_{needed}$  [kWh] is the average needed energy consumption of the EV per day,  $SoC_{barrier}$  [%] is the SoC above which the vehicle is excluded from the aFRR pool and  $E_{battery}$  [kWh] is the total energy volume of the battery.

If  $EC_{needed}$  equals 17.2 kWh [13],  $SoC_{barrier}$  equals 85% and  $E_{battery}$  equals 85 kWh (a regular Tesla Model S), then  $E_{flex}$  equals 4.5 kWh. At a maximum charging rate of 11 kW this would result in less than two ISPs (i.e., 25 minutes) in which EVs charge and thus can provide upward aFRR by stop charging. However, it is evident that when an EV is providing upward aFRR, it is not charging and thus its SoC is not increasing. Therefore, an EV could, if controlled smartly by the BSP, provide aFRR in more than two ISPs (especially in the case of activations in consecutive ISPs).

#### 4.2. Charging profiles and availability for aFRR

To determine the suitability of EVs deployed for aFRR not only the energy consumption per EV per day should be considered. For the TSO it is also relevant to gain insights in when EVs charge, since it is only possible to provide upward aFRR during time intervals in which EVs (would originally) charge. Figure 4.1 shows the share of EVs charging at home per ISP in the Netherlands for a weekday and a weekend day based on [55].

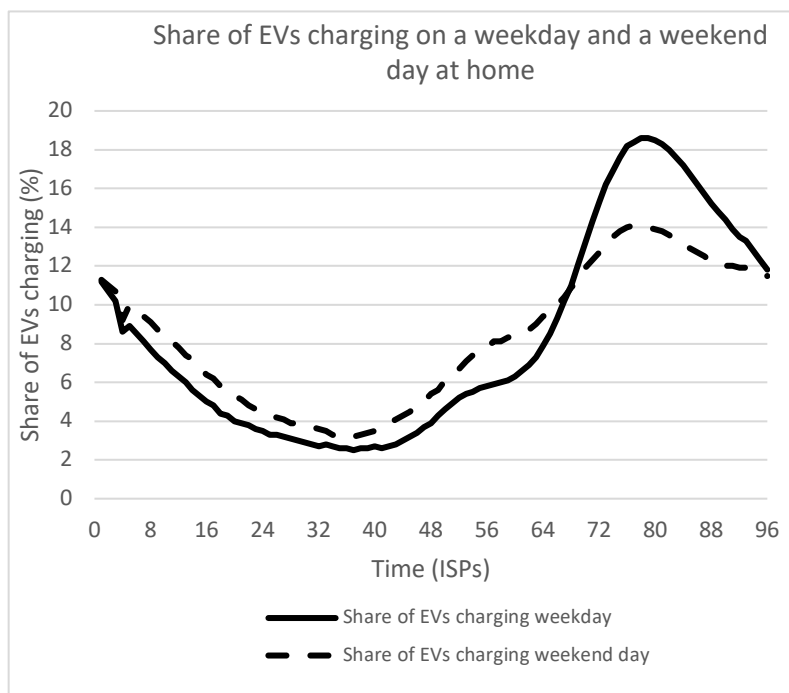


Figure 4.1 The share of EVs charging at home per ISP for a weekday and weekend day. Adapted from [55].

The charging profiles can be used to calculate for every ISP the number of required EVs in the total fleet to be able to deliver 1 MW of aFRR (i.e., have a total charging power of 1 MW). This can be calculated via equation (4.2):

$$EV_{S_{perMW}} = \frac{\frac{1}{CR}}{\left(\frac{EV_{S_{charging}}}{100\%}\right)} \quad (4.2)$$

Where  $EV_{S_{perMW}}$  is the number of EVs required to provide 1 MW of aFRR,  $CR$  [MW] is the individual maximum charging rate retrieved from [13] and  $EV_{S_{charging}}$  [%] is the share of EVs charging in the specific ISP based on [55].

The maximum charging rate,  $CR$  varies significantly per type of EV, which subsequently affects the  $EV_{S_{perMW}}$ . Therefore,  $EV_{S_{perMW}}$  is analysed for three different types of EV with different charging rate. Similarly as in [13] this is done for a Tesla Model S (11 kW), a Nissan Leaf (6,6 kW) and an Opel Ampera (3,7 kW). Figure 4.2 shows based on the charging profile in [55] and equation (4.2) how many EVs the total fleet should entail to deliver 1 MW per ISP for each type of EV. It is important to emphasise that this analysis is based on average values and on current charging rates and profiles. Hence, it is mainly depicted to roughly obtain an understanding of the magnitude of order of required EVs per MW.

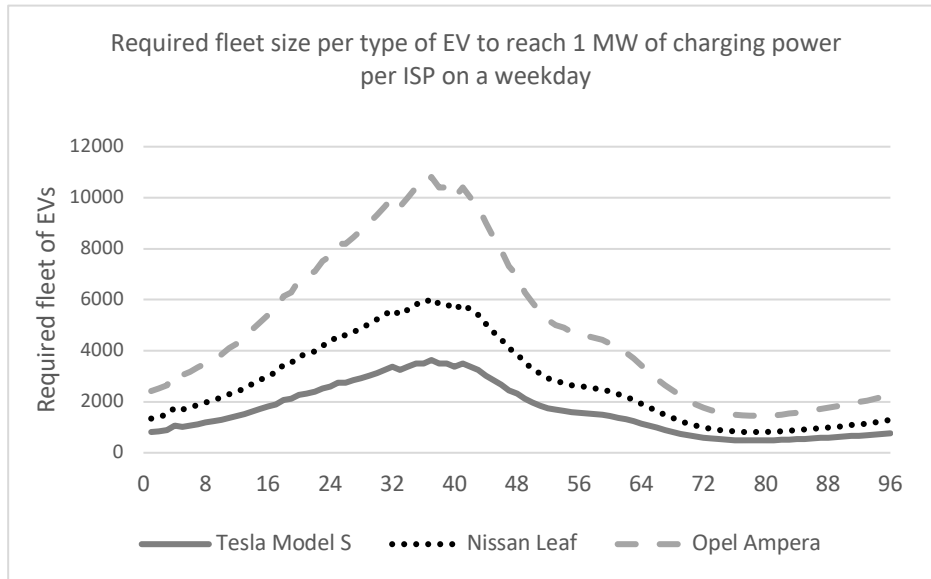
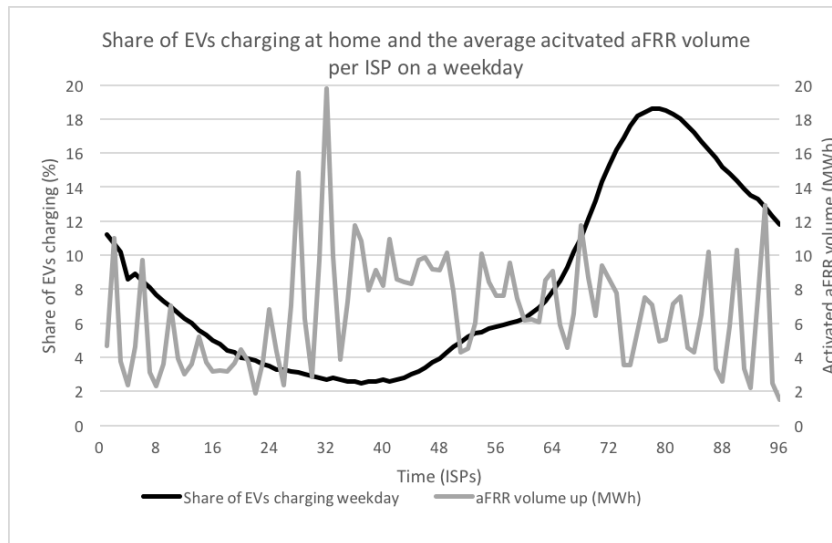


Figure 4.2 The required fleet size per type of EV to reach 1 MW per ISP.

Figure 4.2 shows that the number of required EVs to reach 1 MW varies significantly per ISP and per type of EV. Most EVs are needed during ISP 37 (9:00-9:15) (i.e., 3636 Tesla EVs and 10811 Opel EVs) and fewest are needed during ISP 78 (19:15-19:30) (i.e., 489 Tesla EVs and 1453 Opel EVs). Comparing figure Figure 4.2 with Figure 4.3, which depicts the average upward aFRR volume and the average home charging profile, shows that the two ISPs of the

highest upward aFRR activated volume correspond with ISPs in which the share of EVs that charge is rather low. And hence, the number of the total required fleet is rather high.



*Figure 4.3 Average share of EVs charging at home and the average activated upward aFRR volume per ISP.*

These analyses suggest that, decentralised assets with complementary demand profiles should be considered. However, it should be noted that the peaks in activated aFRR volume are, as described in Section 2.3.2, mainly caused by the fact that the ramp-up/down rate of conventional power plants is often too low to adequately follow the large steps in indicated production at hourly time intervals due to day-ahead trading. In the future the course of average aFRR volume per ISP could change, because of two main reasons. Firstly, the time intervals on the day-ahead market should be equalised to the length of ISPs in 2025 according to the Clean Energy Package. Secondly, a shift in the production portfolio from conventional power plants to renewable energy sources, is assumed to be escorted by different challenges. For instance, rapidly changing weather conditions can result in inaccurate production predictions and thus potentially to higher imbalance volumes.

Nevertheless, it could be assumed that it is beneficial to have assets with aFRR providing capacity in all ISPs regarding reliability of the grid from the perspective of the TSO and regarding the maximisation of aFRR (and thus financial) potential for the BSP. For EVs, the aFRR capacity could be distributed more evenly over the day in two ways. Firstly, smart charging could result in a more widespread demand profile, which could reduce the required number of EVs in the fleet per MW. Another method is also deploying EVs with different demand profiles. Figure 4.4 shows the normalised demand of EVs that (also) charge at work and EVs that do not charge at work. The profiles have a (partial) complementary character in the sense that the normalised demand of EVs that plug in at work is relatively high in the morning compared to the normalised demand of EVs that do not plug in at work in the morning. Therefore, it should be considered to add vehicles that charge at work to the pool of aFRR providing assets in case of scaling up.

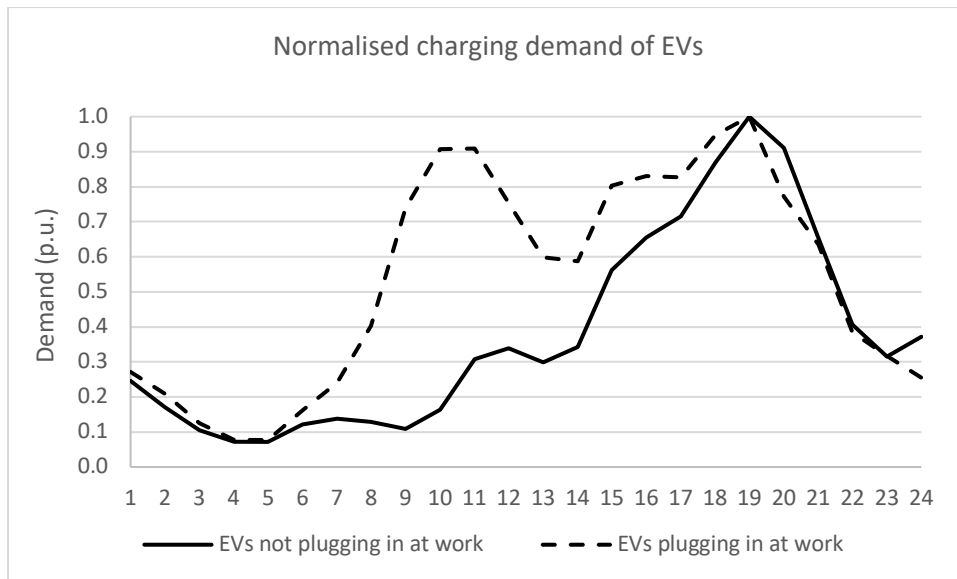


Figure 4.4 Normalised demand of EVs that plug in at work and EVs that do not. Adapted from [56].

### 4.3. Pilot processes

In this section the pilot processes are described. This entails the methods of planning, bidding, activation, verification and settlement as well as the level of detail and frequency of the data that is registered on the blockchain.

#### 4.3.1. Operational planning and scheduling

If Tesla EV owners, that participate in the pilot project, plug their car in their residential CP, then they can enable smart charging through an application developed by Vandebroun. In this application customers can indicate their estimated time of departure. The BSP has the flexibility to determine the charging process, provided that a SoC of 100% is reached at the end of the charging session.

Regarding the planning of the bids, the aggregator estimates in which ISPs it will have enough EVs available to provide aFRR to reach the minimum bid size of 1 MW. The aggregator places its bids on the blockchain including the bid size, the bid price, minimum regulation rate and the specific ISP. The bids are retrieved from the blockchain and converted into a EDINE format to make it compatible with TenneT's regular processes and systems. Similarly, the regular GCT of thirty minutes applies in the pilot and bids are placed on the regular bid ladder.

#### 4.3.2. Real-time operations

In the traditional aFRR procedures, the TSO communicates setpoints via leased lines and Remote Terminal Units (RTU). However, the current RTUs are not able to log setpoints on the blockchain. Hence, in the pilot a virtual RTU (vRTU) is used. Intermediate systems and steps are implemented to communicate from the vRTU to the blockchain, so that the setpoints sent by the TSO are logged on the blockchain in case of an activated bid. The BSP

processes these setpoints, selects the EVs from the available pool<sup>7</sup> and sends signals via the Tesla cloud to change their charging behaviour (e.g., stop charging). The minimum regulation rate of the pool is 21% per minute which is higher than the regular minimum regulation rate requested by the TSO [8]. At the end of the activated bid the TSO sends the final setpoint (i.e., setpoint-0) to the BSP, where after the BSP sends a signal to the selected EVs to resume their original charging course.

#### 4.3.3. Verification and financial settlement

Despite the fact that aFRR is provided with different assets and via blockchain technology, the verification and settlement procedures are the same as for other BSPs. This means that the settlement is based on the setpoints as sent by the TSO. This assumes that aFRR is provided as demanded. To verify whether this actually happened the TSO's process specialists execute ex-post visual analyses<sup>8</sup>. In this verification process, the actual aggregated power output is compared to the sent setpoints and the reference signals as described in Section 2.3.1.

#### 4.4. Data exchange

This section describes which data is shared in the pilot as well as the level of detail and the frequency. The pilot helps the TSO to obtain a better understanding and overview of the data that is needed to verify correct aFRR delivery from decentralised assets. Table 4.1 shows an overview of the type, frequency and level of resolution of the exchanged data.

*Table 4.1 An overview of the type, frequency and level of resolution of the data exchanged in the pilot*

Type of data	Frequency	Level of resolution
<b>Aggregated power output</b>	4 seconds	Pool level
<b>Asset power output</b>	1 minute	Asset level
<b>State of Charge</b>	1 minute	Asset level
<b>Reference signal (+1 minute)</b>	4 seconds	Pool level
<b>Reference signal (+2 minutes)</b>	4 seconds	Pool level
<b>Reference signal (+5 minutes)</b>	4 seconds	Pool level
<b>Reference signal (+15 minutes)</b>	4 seconds	Pool level
<b>Asset status</b>	Once per status change	Asset level
<b>Bid placement</b>	Once per bid	BSP level
<b>Setpoints</b>	Once per setpoint change*	BSP level

\* Only during ISPs of activated bid(s)

<sup>7</sup> In the pilot, all EVs from the available pool are selected due to the limited fleet size (approximately 100 EVs in total fleet). In the future, if the capacity in the available pool is higher than the bid size, it can select a part of the charging EVs to provide aFRR.

<sup>8</sup> Note that actually only the provision of aFRR via contracted parties is verified in practice. For voluntary bids, the TSO assumes that BSPs are incentivised to provide aFRR as demanded as they are corrected on their imbalance position as BRP likewise. In section 6.2 is discussed why this assumption perhaps needs revision in the future.

The level of detail of which information is shared, is rather high (e.g., four different reference signals every 4 seconds). This is mainly to assess which data is valuable for the TSO to ensure aFRR is provided correctly and which data is perhaps redundant. It should be kept in mind that the number of decentralised assets providing aFRR in the future is supposed to be significantly higher, which increases the need for efficient non-redundant data exchange. The proposed method in Chapter 5 could help in this respect.

#### 4.4.1. Statuses

The assets are allocated different statuses by the BSP. By allocating a status, the (charging) behaviour of the vehicles, analysed in Section 4.5.2 can be understood more easily. Table 4.2 shows the four statuses that can be allocated to the assets. Note that if an EV owner has not granted permission to a flexible charging session no status is allocated and no data on the blockchain is logged at all.

*Table 4.2 The different statuses of the assets in the pilot.*

Asset statuses	Description
<b>4) Vehicle outside aFRR pool</b>	Allocated when the EV is not available for aFRR anymore. For instance if SoC > 85%, if a SoC of 100% cannot be reached before departure time in combination with aFRR provision or if an owner plugs out earlier than expected.
<b>3) Vehicle in aFRR pool</b>	Default status when an EV is plugged in and the owner granted permission for a flexible charging session.
<b>2) Vehicle allocated to a bid</b>	Assigned when an EV is allocated by the BSP to a placed bid .
<b>1) Vehicle activated</b>	Assigned when an EV is activated for aFRR (i.e., is forced to stop charging).

#### 4.5. Data analyses

To obtain a better understanding of the quality of the aFRR provision with EVs and the current verification mechanism different data analyses are contemplated. The data is exported from the blockchain and analysed in Python. The first part of this sections addresses the aggregate power output and the reference signal in a time interval with multiple bids. Hereafter, the individual response of EVs to aFRR activation is in the same interval is analysed.

##### 4.5.1. Aggregate power and reference signal

In the pilot new assets (i.e., EVs) and new ICT (i.e., blockchain) are used for aFRR provision. Nevertheless, the verification process is, similar to in the traditional system, based on the aggregate power output, the reference signal and the delta setpoints sent by the TSO. Figure 4.5 shows the aggregate power output and reference signals for a time interval of seven hours. Within this time interval six bids are activated which can be observed by the rapid changes in power to 0 kW. Note that the numbers on the y-axis are intentionally missing as requested by the TSO, because of data confidentiality issues. It should be considered that charging is regarded as a negative power output. Hence, lower data points on the y-axis represent more negative values and thus more charging power. In this thesis,

an increase in power output is considered as a more negative power output (i.e., more EVs charging) and a decrease is regarded as a less negative power output (i.e., less EVs charging).

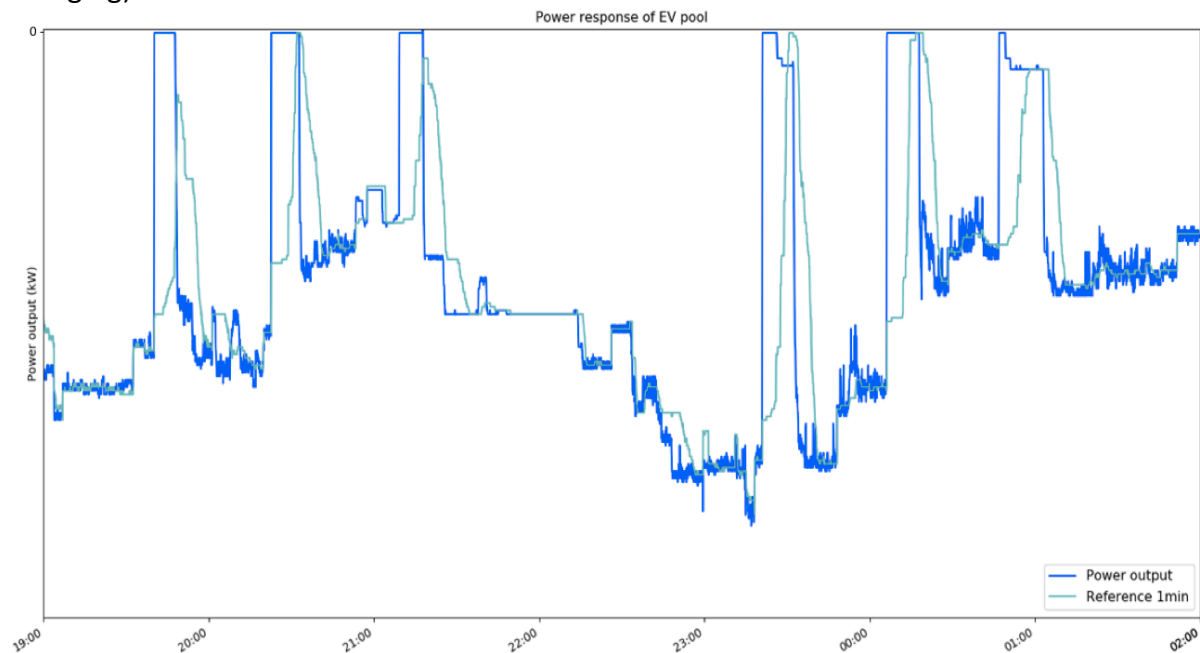


Figure 4.5 The course of the reference signal and the aggregate power output during a time interval in which six bids are activated.

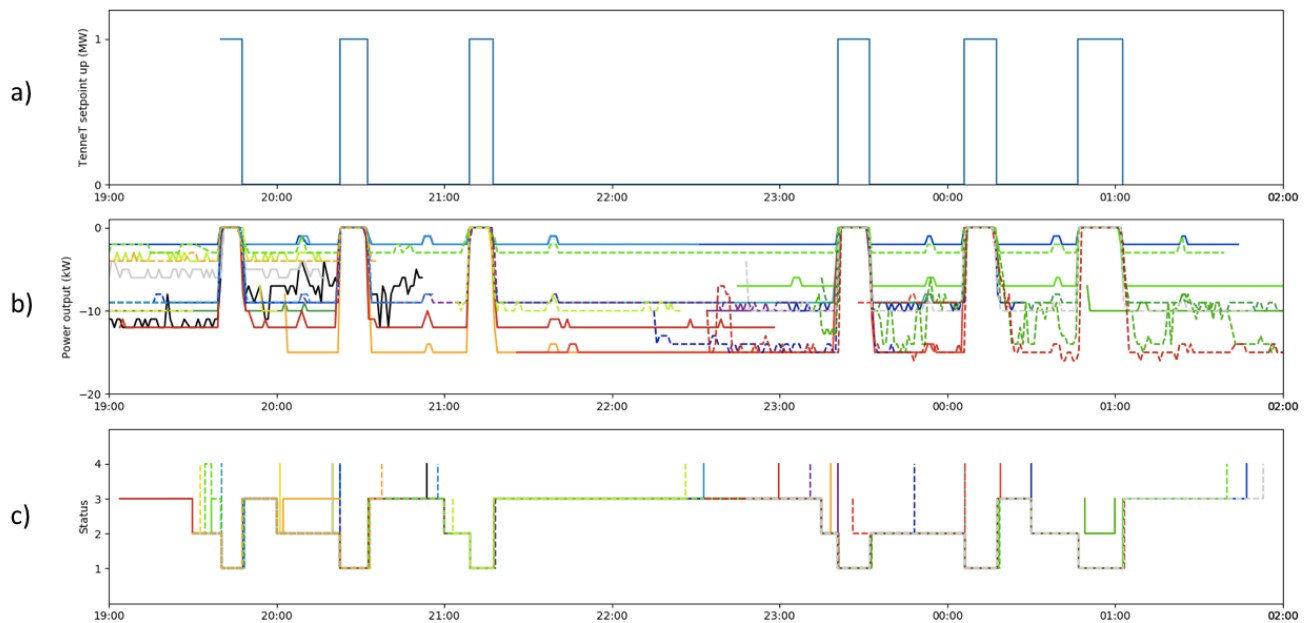
Figure 4.5 provides multiple insights. Firstly, it can be noted that the assets respond very rapidly in case of activation, considering the steep decrease and increase in power output. Secondly, it can be observed that during the fourth and the sixth activation the power output increases slightly during the activation. This can be explained by EVs plugging in during the activation. Figure 4.6 provides more information regarding this issue. Thirdly, Figure 4.5 provides insights in the functioning of the reference signal. It is not clear how the BSP exactly constructs its reference signal, but interpreting the data gives some indication of the used algorithms. The reference signal follows the power output, but lags somewhat behind. This can mainly be observed during activations, as the power output changes very rapidly. It is expected that the BSP uses the most recent actual power output to construct the reference signal for one minute in the future. Outside activations this is quite accurate due to relatively stable power output. However, the fact that the reference signal is also adapted based to the actual power output during activations makes it rather useless. The idea of this verification method is that the difference between the power output and the reference signal equals the provided aFRR. Ergo, this method does not work with the current algorithms employed for constructing the reference signal as the provided aFRR is reflected in the reference signal.

In addition to the fact that the current method of constructing the reference signal is not suitable, verifying aFRR volumes by means of a reference signal has other, more general, disadvantages. (i) The reference signal is in its essence a prediction rather than a representation of facts, which always results in a degree of uncertainty, that seems to be higher for EVs than for power plants due to more external unaffected factors (e.g., EVs plugging in/out). (ii) Prior research has shown that market parties sometimes do not comply

with the requirement to send the reference signal a priori and build up their reference signal a posteriori for their own benefits (gaming) [23]. (iii) The current verification process consists of a post non-automated time consuming visual analyses. Therefore, Chapter 5 proposes an alternative method.

#### 4.5.2. Individual response of EVs to aFRR activation

In order to determine the individual response of EVs to aFRR activation, the same time interval as in Figure 4.5 is analysed. In this time interval, six bids are activated. Figure 4.6 a) shows the course of the upward setpoints sent by the TSO, Figure 4.6 b) shows the individual power output of the EVs and Figure 4.6 c) shows the status of the EVs.



*Figure 4.6. An overview of the sent setpoints (a), the individual power output (b) and the status of the assets (c).*

Figure 4.6 b) shows that the assets respond well to the sent setpoints in a), as the power output of all EVs goes rapidly to 0 kW during activation. The length of the activation is as demanded as well. Analyses of other time intervals show that EVs sometimes deactivate (i.e., resume charging) sooner than demand, but this does not apply to this analysed time interval.

In the fourth and sixth activation it can be observed in Figure 4.6 b) that an EV plugs in, which is also mentioned below Figure 4.5. During the fourth activation this EV is represented by the red dashed line and in the sixth activation by the green line that does not equal 0 kW. This can also be seen in Figure 4.6 c) as the red dashed line during the fourth activation and the green line in the sixth activation are the only lines that do not have status 1 (i.e., vehicle activated). The TSO is currently still discussing what should happen (e.g., activate immediately or not) with EVs that plug in or out during activation. Hence, no requirements exist yet regarding this issue.

#### 4.5.3. Lessons learnt from data analyses

Figure 4.5 and Figure 4.6 show examples of the contemplated data analyses and how the quality of the aFRR provision by EVs is assessed. These data analyses are executed on a daily basis. Some general lessons learnt from these analyses are described below.

There are several reasons why assets do not provide aFRR as requested. These reasons are divided in why EVs do not activate or deactivate correctly. For both processes the reasons are described below.

##### *Incorrect activation (i.e., stop charging)*

- The Tesla cloud overrules the commands of the BSP. At the time of writing it not clear why this sometimes occurs.
- The asset is unresponsive and does not process signals from the BSP/Tesla cloud. At the time of writing it is not clear why this sometimes occur.
- The BSP does not process and/or transfer setpoints correctly due to backend issues.

##### *Incorrect deactivation (i.e., resume charging)*

- Assets deactivate too soon. This was caused by a safety mechanism incorporated by the BSP that sent a 0-setpoint at the end of an ISP. In the case of activated bids in consecutive ISPs this resulted in assets that were deactivated too early. This issue is solved after the data analyses.
- Assets do not deactivate/resume charging when the BSP sends a 'stop activation' signal. This is currently solved by the BSP, by sending an active 'start charging' command, after receiving the 0-setpoint, to resume charging.

Based on abovementioned and other observations some points of improvement are identified.

##### *Points of improvements*

- Obtaining a better understanding of why assets are sometimes unresponsive.
- Gathering more insights in why the power output of the individual assets is often rather erratic.
- More collaboration between the BSP and Tesla to better understand why Tesla sometimes overrules signals sent by the BSP or decrease dependency on the Tesla cloud (e.g., communicate signals via CP).
- Implementation of new algorithms by the BSP to increase the reliability of the reference signal or explore other ways to verify aFRR provision.

#### 4.6. Summary

In this chapter, characteristics of EVs such as the average daily charging profile and charging rates for different types of EVs are discussed and analysed. These analyses are compared to trends in activated aFRR volume analysed in Section 2.3.2. This comparison shows that it is recommendable to also deploy assets with complementary demand profiles (e.g., EVs that charge at work) to lower the number of required assets per ISP during the day.

Furthermore, the pilot processes for each phase (i.e., planning and scheduling, real-time operations and verification and settlement) are described. In addition, the shared data is

analysed regarding frequency, level of resolution to get a better understanding of what is needed for the TSO regarding data exchange to verify aFRR provision in the investigated pilot. This is also taken into account in the proposed future concepts in Part III.

This chapter also contains data analyses that show how the EVs respond on aFRR activation in practice. More specifically, the responses of assets in individual power output to setpoints are analysed. This contributes in answering sub question 1: *Is the utilisation of EVs for aFRR provision technically feasible?* The analyses show multiple activated bids in which the EVs respond as demanded regarding the timing of the response and the minimum required regulation rate. Therefore, the utilisation of EVs for aFRR provision seems to be technically feasible, keeping in mind that the number of EVs in the investigated pilot (and thus in the data analyses) is still relatively small and should be significantly increased.

The chapter also identifies possible improvements. On pool level, the level of the quality of the reference signal is yet insufficient and on individual level various reasons are described that cause EVs to react differently (or not at all) to the setpoints sent by the TSO. This information is used to gain insights in order to answer sub question 3: *What are possible improvements with respect to the investigated pilot and is it possible to expand the concept for other purposes?* Section 7.1 addresses this question.

The information in this chapter is presented to analyse the current concept of the deployment of EVs for aFRR provision. The chapter provides insights that are used to answer sub question 2 and (partially) sub question 3. In addition, these insights are used for the construction of the proposed future concept, which is described in Part III.

## Part III

Proposed future concepts

## 5. Proposed future aFRR verification method

In this chapter an alternative method is proposed to verify aFRR that could potentially be deployed for future applications. This chapter describes the theoretical core of the suggested approach that aims to (partially) replace the current visual non-automated process.

### 5.1. Explanation of the proposed verification method

Figure 5.1 shows an example of an activated bid with a regulation rate of 20% per minute and a bid size of 5 MW to explain the proposed method.

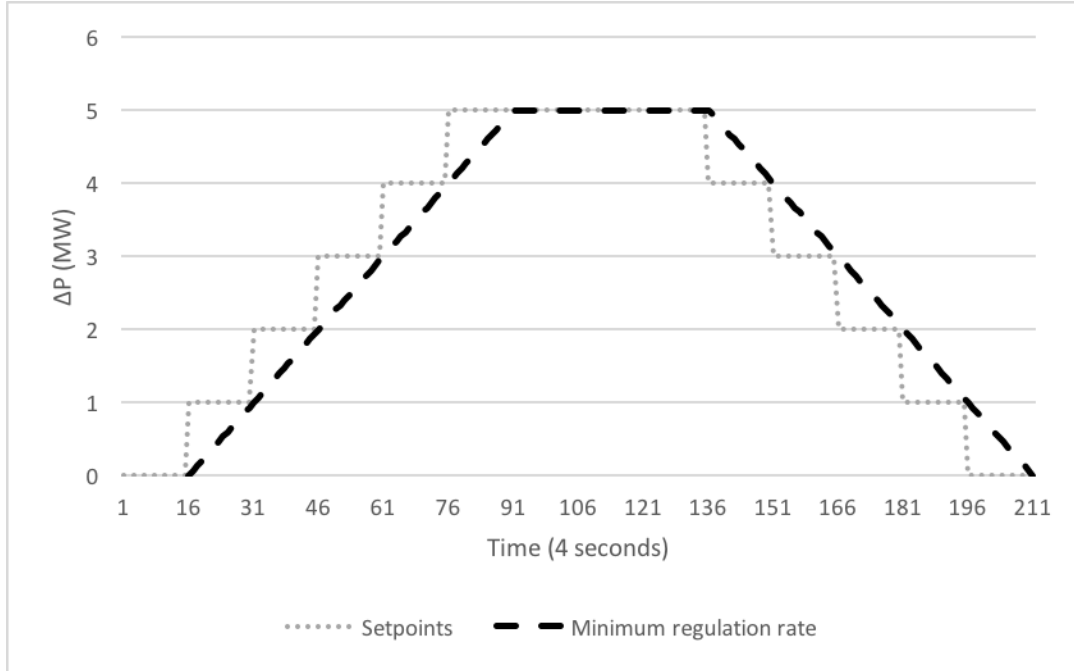


Figure 5.1 An overview of the course of setpoints and the minimum required reaction of the power output for an activated bid of 5 MW with a regulation rate of 20% per minute where time is depicted as a discrete variable with intervals of four seconds.

The time interval of four seconds in Figure 5.1 is chosen, because it is the same interval that is used by the TSO to update the values of the setpoints. The y-axis shows the change in power output of the aggregation of reserve providing assets, which is considered as aFRR provision. The grey dotted line depicts the setpoints sent by the TSO and the black dashed line represents the course of the change in power output when the minimum regulation rate of the bid would be followed.

In Figure 5.1, three phases can be distinguished. In the first phase the upward aFRR setpoints increase (0 to 5 MW). In the second phase the upward aFRR setpoints remain constant at 5 MW. And in the third phase the upward aFRR setpoints decrease (5 to 0 MW). For each phase a method is proposed to automatically verify whether aFRR provision is provided sufficiently for each time interval taking into account the setpoints, regulation rate and total bid size.

### 5.1.1. Used equations and variables

Time in this method is defined as discrete value so that:

$\tau = 4 \text{ [sec]}$ , or: the size of the intervals.

$t = 1, 2, 3, \dots, N$ , where  $N$  is the number of time intervals per day (i.e.,  $N = \frac{60 \cdot 60 \cdot 24}{\tau} = 21600$ )

The minimum required gradient of the change in change in power output per minute is defined by equation 5.1:

$$\alpha = \frac{\text{regulation rate}}{100\%} * \text{bid size} \quad \text{in [MW/min]} \quad (5.1)$$

Where,  $\alpha$  [MW/min] is the minimum required gradient of the change in power output, *regulation rate* [%/min] is the minimum regulation rate that each BSP has to indicate per bid with a minimum regulation rate of 7%/min required by the TSO and *bid size* [MW] is the indicated bid size by the BSP. In the example of Figure 5.1, the indicated regulation rate is 20 %/min and the bid size is 5 MW. This results in a  $\alpha$  of 1 MW/minute.

The minimum required gradient of the change in power output per time interval (i.e., 4 seconds) is defined by equation 5.2:

$$\alpha' = \frac{\alpha}{60/\tau} = \frac{\alpha}{15} \quad \text{in [MW/\tau]} \quad (5.2)$$

In this example  $\alpha'$  equals  $\frac{1}{15} \text{ MW per time interval } \tau$ .

The general idea of the verification method is that during time intervals in which the setpoints increase or decrease, the change in power output should always be in the range of the minimum required gradient (represented by the black dashed line in Figure 5.1) and the received setpoints (represented by the grey dotted in Figure 5.1). In case the setpoint values remain constant for a longer time interval (e.g., interval 91 to 136 in Figure 5.1), the power output should equal the received setpoints. The next sections describe a model by which this can be verified automatically.

The variables below relate to the setpoints sent by the TSO and received by the BSP. The values (e.g., 1 MW, 2 MW, 3 MW etc.) of these setpoints are updated on a 4 seconds interval.

$S_X(t)$   
= the latest known (and thus applicable) setpoint value  $S$  [MW] at current time  $t$

For example in Figure 5.1:  $S_X(16) = 1 \text{ MW}$ ,  $S_X(31) = 2 \text{ MW}$  and  $S_X(151) = 3 \text{ MW}$

$S_{X-1}(t)$  = the setpoint value [MW] of the setpoint sent **before**  $S_X(t)$   
 $S_{X+1}(t)$  = the setpoint value [MW] of the setpoint sent **after**  $S_X(t)$

In a phase of increasing setpoints (e.g.,  $t=16$  to  $t=76$  in Figure 5.2),  $S_X(t)$  is larger than  $S_{X-1}(t)$ . For example:

$$S_X(31) = 2 \text{ MW and } S_{X-1}(31) = S_X(16) = 1 \text{ MW}$$

$$S_X(46) = 3 \text{ MW and } S_{X-1}(46) = S_X(31) = 2 \text{ MW}$$

In a phase of decreasing setpoints (e.g.,  $t=136$  to  $t=196$  in Figure 5.2)  $S_{X-1}(t)$  is larger than  $S_X(t)$ . For example:

$$S_X(151) = 3 \text{ MW and } S_{X-1}(151) = S_X(136) = 4 \text{ MW}$$

$$S_X(166) = 2 \text{ MW and } S_{X-1}(166) = S_X(151) = 3 \text{ MW}$$

The variables below relate to the time on which setpoints are received.

$t'_{S_X(t)}$  = time  $t$  on which setpoint  $S_X(t)$  is received  
 $\Delta t = t - t'_{S_X(t)}$ , or the time between **current** time  $t$  and  $t'_{S_X(t)}$ , on which  $S_X(t)$  is received

For example in Figure 5.1:

At  $t = 50$ :

$$S_X(50) = 3, t'_{S_X(50)} = 46 \text{ and } \Delta t = 50 - 46 = 4$$

And at  $t = 70$ :

$$S_X(70) = 4, t'_{S_X(70)} = 61 \text{ and } \Delta t = 70 - 61 = 9$$

Regarding the (change in) power output several variables are defined as well:

$P(t) = \sum_{i=1}^k P_i(t)$ , or: the power output at time interval  $t$  of the aFRR pool, with  $k$  number of EVs in the aFRR pool.

$P_0$  the power output of the aFRR pool [MW] when the **first** setpoint of the activated bid is received. In Figure 5.2, this is at  $t=16$  and thus  $P_0 = P(t'_{S_X(16)}) = P(16)$

$\Delta P(t)$  [MW] =  $P(t) - P_0$ , or: the difference between the actual power output at interval  $t$  of the pool and  $P_0$ ,

As mentioned earlier, three phases can be distinguished in Figure 5.2. A phase with increasing upward setpoints, a phase with constant upward setpoints and a phase with decreasing upward setpoints. For each phase is now mathematically shown how it can be verified if  $\Delta P(t)$  is in the bandwidth of the setpoints and the minimum regulation rate and thus sufficient.

### **Phase 1: Increasing upward aFRR setpoints**

The first condition is:

$$S_X(t) > S_{X-1}(t) \quad (5.3)$$

The second condition is:

$$\Delta t \leq \frac{1}{\alpha'} \quad (5.4)$$

Equation 5.3 shows that the upward setpoints are increasing. Equation 5.4 shows the number of intervals after which a setpoint with a new value would have been sent if the activation would be further increased by the FVR. For the example in Figure 5.1, this means that every 15 time intervals the value of a setpoint changes in case of increasing or decreasing setpoints. Hence, if  $\Delta t$  is smaller or equal, then phase 1 or 3 is applicable, else phase 2 is.

Then for phase 1, it can be derived that response of the BSP to the setpoints is sufficient when:

$$\Delta P(t) \leq S_X(t) \wedge \Delta P(t) \geq S_{X-1}(t) + \alpha' * \Delta t \quad (5.5)$$

As is relevant from  $t=16$  to  $t=91$  in Figure 5.1.

### ***Phase 2: Constant upward aFRR setpoints***

The only condition is:

$$\Delta t > \frac{1}{\alpha'} \quad (5.6)$$

Equation 5.6 shows that more time intervals have passed than the number of time intervals after which a setpoint with a new value would have been sent according to the minimum regulation rate and bid size. This means that the upward aFRR setpoints remain at a constant value. The response of the BSP to the setpoints is then sufficient when:

$$\Delta P(t) = S_X(t) \quad (5.7)$$

As is relevant in time intervals  $t=91$  to  $t=136$  in Figure 5.1. Note: the first setpoint of 5 MW is already sent at  $t=76$ , but equation (5) does not apply yet until  $t=91$ . Therefore, this phase starts at  $t=91$  and not at  $t=76$ .

### ***Phase 3: Decreasing upward aFRR setpoints***

The first condition is:

$$S_X(t) < S_{X-1}(t) \quad (5.8)$$

The second condition is:

$$\Delta t < \frac{1}{\alpha'}$$

Where, equation (5.8) shows that the upward setpoints are decreasing and where equation (5.9) is used similarly as in phase 1.

Then, it can be derived that response of the BSP to the setpoints is sufficient when:

$$\Delta P(t) \geq S_X(t) \wedge P(t) \leq S_{X-1}(t) - \alpha' * \Delta t \quad (5.9)$$

As is relevant in  $t=136$  to  $t=211$  in Figure 5.1.

Figure 5.2 shows the proposed verification method for the different phases within an activated bid.

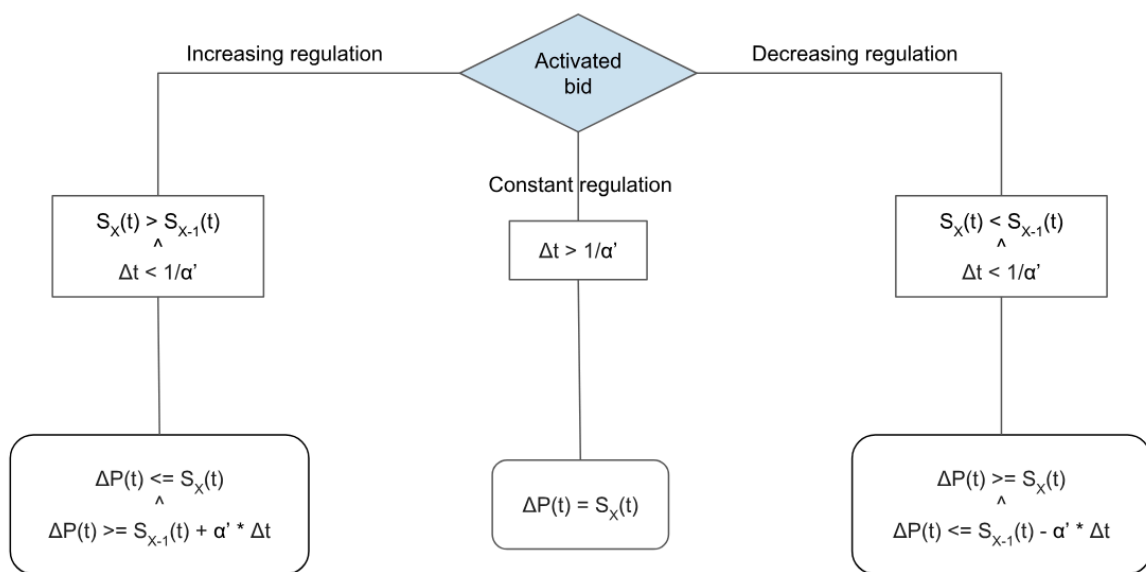


Figure 5.2 A flow chart that depicts the proposed aFRR verification method.

Note: this is a theoretical approach for the verification of aFRR by multiple flexibility providing assets. Of course, an error margin or alike mechanisms should be considered to make this work in practice. The proposed theory serves as a method that could be used to determine design variables in a succession of the pilot such as the desired resolution of logged time intervals, the allowed error margins etc.

One example of such a design variable that has to be incorporated is the time delay in sending and receiving signals. Once this design variable is determined, it is relatively easy to incorporate this in the proposed verification method. For instance equation (5.5) in phase 1 could be adapted as shown in equation (5.10).

$$\Delta P(t - \varepsilon) \leq S_n \wedge \Delta P(t - \varepsilon) \geq S_{n-1} + \alpha * \Delta t \quad (5.10)$$

Where  $\varepsilon$  reflects an incorporated time delay.

## 5.2. Implications of proposed aFRR verification method

This section shortly describes the implications of the proposed aFRR verification method regarding advantages compared to the current verification method as well as some requirements to actually implement the proposed method.

### 5.2.1. Advantages of proposed method

The proposed method enables the possibility to (at least partly) automate the aFRR verification process. This results in a less time consuming process and more activations that can be monitored. Especially in a future with more BSPs and perhaps more (and smaller) aFRR bids it can be a burden on the TSO to verify (all) aFRR activations manually.

A second advantage is the fact that the proposed method does not depend on the accuracy of the reference signal (as is the case in the current method). Analysing the pilot data so far, shows that the current algorithms behind the reference signal do not result in an accurate 'prediction' of the power output. Constructing a reference signal for a fleet of EVs could be more difficult than for a conventional power plant, due to more external factors (e.g., EVs plugging in/out unexpectedly), although the impact of such unexpected events could be smaller in the future with larger pools. The proposed method can potentially eliminate the need for a reference signal as the only required known variables are the actual power output, the (timing of sending) setpoints, the bid size and the minimum regulation rate.

The third advantage also relates to the needed variables for the proposed method. Theoretically abovementioned variables only need to be communicated during an activation. This reduces the amount of data that is exchanged compared to the current process. For instance, as mentioned before, the reference signal is currently sent every four seconds, also in case of no activation, for one, two, five and ten minutes in the future. Exchanging less data is especially beneficial in combination with blockchain technology in terms of the transaction rate, required storage capacity and the required energy to keep up the system.

### 5.2.2. Requirements of proposed method

As mentioned before, the proposed method is a theoretical approach. Before it can be implemented, design variables (e.g., allowed error margins) based on experiences from practice should be taken into account. This relates for instance to time delays due to communication, physical limitations of assets and (partially unavoidable) associated errors in aFRR response. Another variable that has to be determined is the level of frequency the TSO wants the BSP to log data. This could be per time interval (i.e., every four seconds), but perhaps per five, ten or fifteen time intervals is also sufficient for the TSO. These design variables could be considered in case of a continuation of the pilot.

Besides it should be clear how BSPs are supposed to react on unforeseen events such as unexpected plugging in/out of EVs during aFRR activation. The proposed method only takes the (change in) power output into account of vehicles that are activated for aFRR. In the pilot, as described in Section 4.4.1, these EVs receive status 1 (i.e., Vehicle activated). EVs with status 1 that plug out or become unavailable due to other reasons during aFRR activation do not longer receive status 1. Therefore, the (change in) power output of the

pool of vehicles with status 1 is modified. To compensate for this modification, the BSP could activate other EVs to restore the amount of power output of EVs with status 1.

Vehicles that plug in during an activation were by definition not activated (and thus status 1 is not allocated). Hence, these vehicles do not affect the (change in) power output of the pool of activated assets. Therefore, the EVs that plug in should be able to follow the planned charging behaviour and should not be added to pool of activated assets.

Another requirement to achieve reliable results with the proposed method is high integrity of the input data. It is important that the logged data accurately reflects the aFRR response in reality and that market parties are not able to construct and manipulate the input data. This is where blockchain technology can offer added value. In Chapter 6, a future blockchain architecture is designed that amongst others proposes a method to increase the integrity of the input data.

## 6. Proposed future blockchain architecture

This chapter describes a proposed future blockchain concept for the application in which aFRR is provided by EVs. The method described in Chapter 5, aims to reduce the burden for the TSO with respect to the verification and settlement phase by automation of processes. This chapter links the proposed method to a blockchain architecture to i) increase the integrity of the input data to enhance the reliability of the method proposed in Chapter 5, ii) increase transparency for all relevant stakeholders by agreeing on predefined smart contracts and iii) enable the possibility to incorporate other relevant stakeholders, such as DSOs for congestion management purposes or BRPs that have assets in their portfolio that are operated by other BSPs, to create a solution on a system level.

### 6.1. Architecture of the proposed future concept

The concept is based on transactions that need to be validated by reaching consensus in the blockchain network before they are accepted on the blockchain. Note that transactions are not restricted to monetary transactions, but also include transactions in which purely information is exchanged. It is recommended to implement a relatively light consensus model, as all nodes are registered and identified, to increase transaction speed and to decrease energy consumption. For instance, one could think of a CFT or a PBFT consensus model as described in Section 3.2.3. In the investigated pilot, all data is registered on the blockchain. In a proposed future concept, it could be considered to solely register hashes on the blockchain to reduce the vastness of the exchanged data. By saving the hashes, manipulation of data can always be recognised as described in Section 3.1.2.

In a further future it could be the case that EVs do not have to be controlled by an aggregator, but that a true Economy of Things and Energy of Things emerges and that EVs can independently provide aFRR. This would require a public distributed ledger technology preferably with high scalability, minimum transaction fees and a lightweight consensus model to avoid high energy consumption. For such an application, a DAG (such as the tangle of IOTA, described in Section 3.5) seems the most suitable technology at the moment of writing. However, as these developments are expected further in the future and are thus accompanied with a higher degree of uncertainty, this thesis focuses on an application in which aggregators are still included.

The proposed types of transactions are designed in such a way that two entities are involved in each data log. Therefore, the reliability of the input data increases, since the data of the two independent entities should theoretically be consistent. For example, the first transaction represents the EV connecting with the CP. Both entities register the time, their own hashed ID and the hashed ID of the other entity. According to the CFT or PBFT consensus model, one of the full validating nodes (thus not an EV or CP, but an entity such as a BSP, TSO etc.) is assigned to request to the blockchain network whether these two data logs match. As explained in Section 3.2.3, this results in a voting process by the network in which the votes are replicated and shared amongst the nodes various times to detect any (un)intended inconsistencies in the voting process. If the required majority is achieved and consensus is reached by the network, then the two data logs are transformed into a transaction. This transaction is then logged on the blockchain with the corresponding timestamp.

It should be noted that in the proposed concept, both the EV and CP register data regarding various transactions in order to increase data integrity. This can be complicated in some cases, as not all smart meters in the CPs are yet capable of registering data with the same data resolution as EVs can. However, ElaadNL (the Dutch knowledge centre in the field of smart charging infrastructure) and the Dutch DSOs have decided to start implementing the SMR-5 meters in CPs that are capable of registering every second [57]. Therefore, it is assumed that in future scenarios it is possible to measure power response on a high resolution (e.g., max. thirty seconds) via both the EV and CP.

Figure 6.1 depicts an overview of all proposed transactions and offers a visual representation of the architecture of the proposed future concept

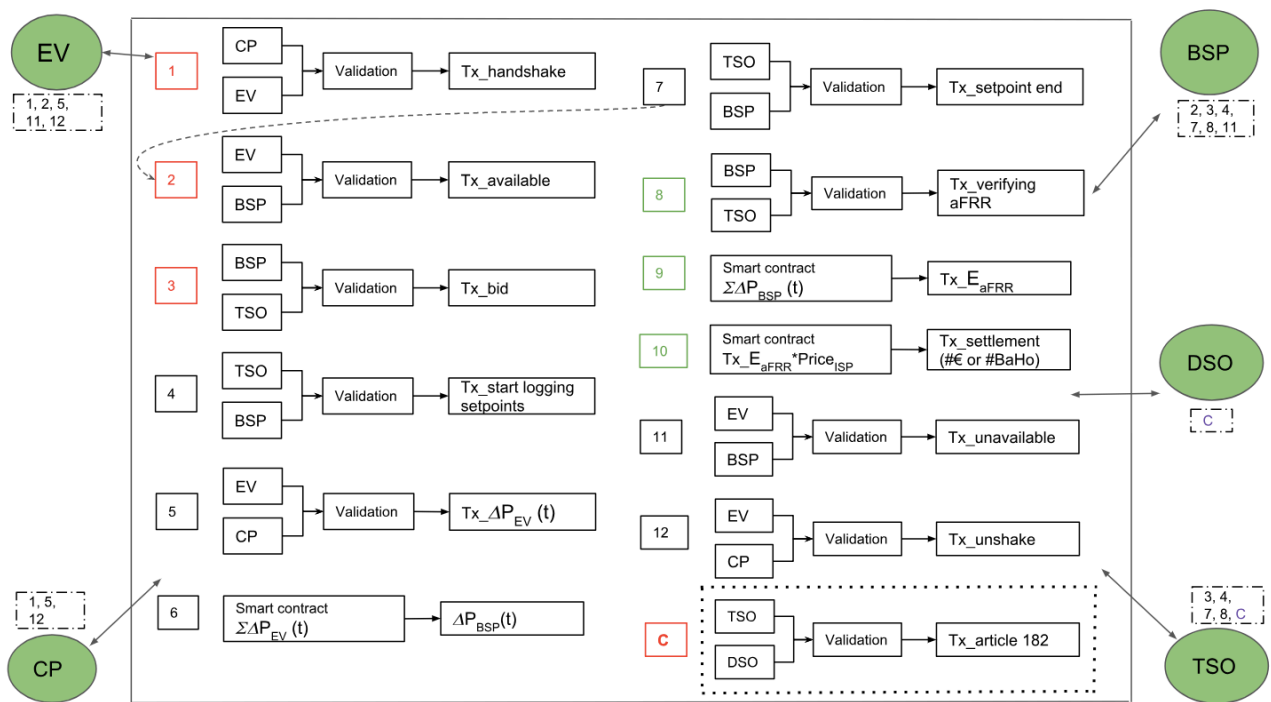


Figure 6.1 A visual representation of the proposed future concept, where squares 1-3 and C represent the planning phase. 4-7 and 11-12 represent the operation phase and 8-10 represent the verification and settlement phase and Tx\_.. represents an individual transaction.

#### 6.1.1. Operational planning and scheduling

Logging transactions on the blockchain starts when the EV plugs into the CP. The EV logs its ID, that is hashed and thereby pseudonymised to avoid privacy issues. It also logs the hashed ID of the CP and the time of plugging in. The CP logs the same information (i.e., hashed IDs of the CP and EV and the time). Then, these two independent data logs are validated by the blockchain network with regard to the consistency and whether the data logs match. If this is the case and consensus is reached via the consensus model, then it results in a virtual handshake between the EV and the CP.  $Tx_{handshake}$  (transaction 1) is then accepted on the blockchain with a corresponding timestamp.

The car owners, not restricted to Tesla cars anymore, can communicate their preferences regarding departure time and the desired SoC via a mobile application. This is preferred over the option of always maximally charging the vehicles (i.e., up to SoC = 100%) that is

yet in play in the investigated pilot. Enabling the option to indicate the desired SoC increases the level of freedom for the consumer and the number of time intervals in which upward aFRR can be provided. Some EVs with a low SoC cannot reach 100% at the moment of their indicated departure time due to time constraints, especially if charging would be postponed to deliver aFRR. Hence, the vehicle cannot join the pool for aFRR provision. However, it might be possible that the consumer is satisfied with a lower SoC (e.g., 85%). This would mean that less charging time is needed, resulting in more time intervals in which aFRR could be provided. In addition, research shows that not charging a Li-Ion battery to a SoC of 100% and reducing the Depth of Discharge (DoD) has a beneficial impact in terms of battery degradation [58].

$Tx_{available}$  (transaction 2) relates to the abovementioned processes. The EV logs whether it is available for aFRR based on permission of the owner. The BSP estimates whether the EV is capable of delivering aFRR based on the desired SoC, the charging rate and the available amount of time. If both the EV and the BSP log that the EV is available for aFRR provision and this is validated by the network, then  $Tx_{available}$  is accepted on the blockchain with a corresponding timestamp.

The last step of the planning phase concerns the bidding process by the BSP. It is proposed to use the same mechanism as described in Section 4.3. However, one important aspect should be considered. In the investigated pilot, data is only exchanged and accessible by two parties on the blockchain (i.e., the TSO and one BSP). Therefore, it is useless to encrypt the information concerning placed bids (e.g., bid price). Nevertheless, in the future multiple BSPs should be added to the blockchain to increase the pool of decentralised assets that can provide aFRR. It is needless to say that BSPs do not want their competitors to know the offered price of their bids. This can be solved by encrypting the transaction as described in Section 3.1.1. In this case, the BSP would encrypt the transaction with the public key of the TSO. Subsequently, only the TSO can decrypt the message by using its private key. Hence, the TSO is the only other participant on the blockchain that knows the bid size and price per BSP. Both the TSO and the BSP can log the hash of the bid, which results –when validated by the network- in  $Tx_{bid}$  (transaction 3).

#### 6.1.2. Real-time operations

Regarding the setpoints sent by the TSO, no adaptations are proposed<sup>9</sup>. At the beginning of an activated bid, the first upward (or downward in future applications as well) setpoint sent by the TSO and received by the BSP is logged as  $Tx_{start\ logging\ setpoints}$  (transaction 4).

From this point in time, and this is an important aspect of the solution, the EV and CP start logging their change in power output,  $\Delta P(t)$ , after aFRR activation on the blockchain according to:

$$\Delta P(t) = P_{activation}(t) - P_0 \quad (6.1)$$

Where,  $P_0$  is the most recent power output of the EV/CP *before* receiving a signal from the BSP to stop charging (i.e., providing aFRR) and where  $P_{activation}(t)$  is the power output

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<sup>9</sup> Except for increasing the resolution of the setpoints, but this is discussed in Section 7.1.

during the activation. Both the EV and the CP keep logging  $\Delta P(t)$  during the activated bid(s) which are, after validation, logged as  $Tx_{\Delta P_{EV}}(t)$  (transaction 5). The proposed verification method in Chapter 5, focusses on the aFRR response on BSP level and not on asset level. Therefore, a smart contract is deployed to automatically aggregate the (change in) power output of the individual assets to the (change in) power output of the pool according to:

$\Delta P_{BSP}(t) = \sum_{EV=1}^k \Delta P_{EV}(t)$ , or: the difference of the power output of the aFRR pool at time interval  $t$  compared to the power output just before aFRR activation, with  $k$  number of EVs in the aFRR pool. This is reflected by transaction 6.

The TSO and the BSP keep logging the setpoints in case the value of the setpoints changes as described in Chapter 5. This continues until the end of the activated bid which is indicated by the setpoint-0, sent by the TSO, which actually consists of two signals; a setpoint-0 for upward regulation and setpoint-0 for downward regulation. Similarly as for earlier setpoints, the TSO and the BSP both log this final setpoint of the activation, which is after validation, referred to as  $Tx_{setpoint\ end}$  (transaction 7). The BSP should then send a signal to the EVs to resume the original charging course.

If the asset is still available for aFRR, depending on its desired SoC and the remaining time until departure, it returns to the status in which it is available to provide aFRR, reflected by  $Tx_{available}$  (transaction 2). If the asset is not able to deliver aFRR in any later time intervals,  $Tx_{unavailable}$  (transaction 11) is logged by the BSP and the EV and the asset is excluded from the aFRR pool. The final transaction is logged when the EV plugs out. Both the EV and CP log this transaction as  $Tx_{unshake}$  (transaction 12).

### 6.1.3. Verification and settlement

This phase starts immediately after the end of ISP of the activation, since the aFRR price is determined at the end of each ISP. Hence, it can occur that transaction 8, 9 and 10 are logged earlier in time than  $Tx_{unavailable}$  (transaction 11) and  $Tx_{unshake}$  (transaction 12) which are still part of the operation phase.

Transaction 8, 9 and 10 relate to the verification and settlement phase. Transaction 8 relates to the verification method described in Chapter 5. To summarise, for increasing, decreasing and constant values of the sent setpoints it could be verified automatically whether aFRR is provided sufficiently according to:

Increasing setpoints:  $\Delta P(t) \leq S_X(t) \wedge \Delta P(t) \geq S_{X-1}(t) + \alpha' * \Delta t$

Decreasing setpoints:  $\Delta P(t) \geq S_X(t) \wedge P(t) \leq S_{X-1}(t) - \alpha' * \Delta t$

Constant setpoints:  $\Delta P(t) = S_X(t)$

Hereafter, a smart contract could be used to automatically calculate the activated aFRR volume (i.e., energy) by summing up the power outputs according to

$E_{aFRR} = \sum_{i=1}^k \Delta P(t)$ , or: the delivered aFRR volume during an activation with  $k$  number of intervals of the activation. This is reflected by transaction 9.

The financial settlement is simply based on multiplying the delivered aFRR volume with the aFRR price of that specific ISP, which can also be automated via a smart contract. For the financial settlement different currencies could be used, varying from the euro to the (yet) imaginary cryptocurrency BaHo. This is represented by transaction 10,  $T_{x\_settlement}$ . It should be noted that the BSP can execute the verification and settlement level process on asset level according the same strategy. The EV and CP log the change in power output due to aFRR activation. How the settlement is arranged is for the BSP to decide. Examples could be; discount on charging sessions, discount on energy contracts or a financial reward at the end of the year. In addition, the distribution of the financial benefits should also be determined by the BSP.

It should be noted that some CPs can only measure on a 15 minutes' level resolution at the time of writing. In this case, the CP is not able to log the power output with a sufficient resolution. Hence, it could be a prequalification criterion formulated by the TSO that aFRR providing assets should be connected to a smart meter that can log data with a sufficient frequency, such as the SRM-5 meter. Or, only the power input of the EV should be logged and used for aFRR verification. Then each 15 minutes it can be checked whether the integral of time of the power output logged by the EV equal the logged energy output by the CP. These results would be less reliable, but still the data integrity is increased as data is logged via two independent parties.

## 6.2. Incorporation of other relevant stakeholders on the blockchain

The proposed future solution offers the opportunity to add other relevant stakeholders to the blockchain. An example of such a stakeholder is the DSO, because i) the DSO can retrieve the data from the CP and ii) the DSO is affected by the deployment of aFRR by decentralised assets, because these assets are usually located in the service area of the DSO and not of the TSO. Another potential stakeholder is the BRP. For both stakeholders is described why and how they could be incorporated on the blockchain.

### 6.2.1. Incorporation of DSOs

Prior research shows that providing aFRR with decentralised assets situated in the low voltage grids, can have a problematic impact on local transformer overloading, cable overloading and voltage deviation [59]. Besides, article 182 paragraph 5 of the guideline on electricity balancing states that: *"Each reserve connecting DSO and each intermediate DSO shall have the right, in cooperation with the TSO, to set, before the activation of reserves, temporary limits to the delivery of active power reserves located in its distribution system. The respective TSOs shall agree with their reserve connecting DSOs and intermediate DSOs on the applicable procedures"* [16].

This indicates the importance of alignment between the TSO and DSO regarding the activation of assets for aFRR situated in the distribution system. A solution could be to integrate the DSO(s) on the blockchain. If the DSO is able to connect the location of the CP to a specific distribution network and it can formulate predefined constraints regarding transformer overloading, cable overloading and voltage deviations, then these constraints can be integrated in smart contracts. Whenever these constraints are violated the option to activate reserve providing assets in the specific distribution network is automatically

excluded by the smart contract and  $Tx_{available}$  is transformed into  $Tx_{unavailable}$ <sup>10</sup>. The proposed solution offers the opportunity to develop procedures related to Article 182 in a predefined, automated and transparent way and is depicted by  $Tx_{article\ 182}$  (transaction C). As, the article states that the DSO has the right to set temporary limits *before* the activation of reserves, this should be incorporated in the operational planning and scheduling phase.

### 6.2.2. Incorporation of BRPs

At the moment of writing, only the provision of aFRR by contracted parties is frequently monitored. For parties that deliver aFRR on a voluntary bidding base, no standard verification processes exist. The BSPs receive the financial compensation based on the setpoints sent by the TSO and the TSO does often not verify whether these setpoints are actually followed. The underlying logic is that the TSO also corrects the imbalance position of the associated BRP based on the sent setpoints. This entails that (even) if BSP A does not follow the sent setpoints, the imbalance position of BRP A is corrected based on these setpoints. Hence, BRP A could come into a (larger) imbalance position. Subsequently, BRP A is settled with the imbalance price, that usually equals the aFRR price<sup>11</sup>. If BRP A would originally perfectly maintain its E-programme, the deviation caused by not providing aFRR (by BSP A) as demanded by the TSO, exactly equals the amount of demanded aFRR provision. In this way, the financial aFRR ‘reward’ is neutralised by the financial imbalance ‘punishment’. Therefore, there would be no financial incentive to *not* follow the setpoints of the TSO. Note that gaming/gambling is still possible as it could be financially beneficial in particular states of imbalance for both BSP A as BRP A, but as this also depends on the imbalance state of the complete system, the associated risks are higher.

However, in the future it is likely that the BSP of an asset is not always the same party as the BRP. This results in a completely different ballgame. Consider a fleet of assets that are controlled by BSP A, but in the portfolio of BRP B. In this scenario, BSP A could be rewarded while not following setpoints/providing aFRR and BRP B could be ‘punished’ with an (larger) imbalance position while not doing anything incorrect. To avoid disputes, it should be clear somehow if BSPs, also in case of non-contracted parties, actually do provide aFRR as demanded. This could be solved by bilateral contracts, but for such a problem, in which different parties do not necessarily trust each other, blockchain technology could offer possibilities. Transaction 9 ( $Tx_{E_{aFRR}}$ ) could also be used by a BSP to prove to a BRP, in case of a potential dispute, the amount of provided aFRR volume. In this way, the TSO would facilitate efficient market processes.

### 6.3. Requirements and advantages of proposed architecture

There are several requirements to implement the proposed architecture in practice. First of all, assets that can register data with a high resolution are preferred as this increases the

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<sup>10</sup> A condition is that the DSO can measure and communicate the current state of its networks regarding overloading and voltage deviations in real-time. At the time of writing this is often not the case. However, DSOs are working on this at the moment (e.g., DALI project at Enexis) [60].

<sup>11</sup> Only in ISPs in which emergency power is activated, the imbalance price is based on the highest price for upward aFRR or upward emergency power and on the lowest price for downward aFRR or downward emergency power [24].

reliability and the integrity of the input data. Secondly, it should be determined what to do with assets that are temporarily not able to register data due to for instance technical or communication issues. Lastly, in the proposed architecture EVs are directly connected to a CP. It should be considered how the method should be adapted in case of a situation in which more devices are connected to the same meter (e.g., when a CP is installed ‘behind the meter’). In this case the measurements of the smart meter are not only based on the EV, but for example also on the energy demand of a heat pump or water boiler. This complicates the task for a BSP, as providing upward aFRR by postponing the charging of an EV could be partially cancelled out on the smart meter if for instance the heat pump would switch on during activation. However, this could be regarded as the risk of the BSP when it wants to provide aFRR with a point of connection to grids with multiple devices behind it.

The proposed method also offers various advantages. Together with the verification method described in Chapter 5, it results in transparent and automated aFRR verification and settlement processes. Besides the reliability of the input data is improved significantly by registering data via two independent entities. Lastly, it provides a solution on a system level that takes into account other stakeholders that are affected by decentralised assets that provide aFRR such as DSOs and BRPs. Table 6.1 gives a clear overview of the differences of the current set-up and the proposed future set-up of the application. Note that ‘verification’ in this table specifically refers to verification of provided aFRR.

*Table 6.1 Differences of the current set-up and the proposed future architecture*

<b>Current concept</b>	<b>Proposed future concept</b>
Centralised verification by TSO	Decentralised verification by consensus mechanism and smart contracts
Off-chain verification process	On-chain verification process
Non-existence of consensus mechanism	Existence of consensus mechanism
Non-automated visual verification	Automated verification
No automation via smart contracts	Efficient automation via smart contracts
Non-transparent verification process	Transparent predefined verification process
Verification based on constructed reference signal	Verification based on actual measurements
Execution of verification process can take multiple days	Near real-time verification process
Low input data integrity due to one-way data input by EV via BSP	High input data integrity due to two-way data input by EV via BSP and by CP
Complicated to involve other relevant stakeholders (e.g., DSOs and BRPs)	Less complicated to involve other relevant stakeholders (e.g., DSOs and BRPs)

# Part IV

Determining implications

## 7. Conclusion

In this thesis the practical implementation of EVs and blockchain technology for aFRR provision is analysed from a theoretical perspective. The outcomes of the thesis shed light on the functioning of the current investigated pilot and on potential adaptations to improve and expand the concept. More specifically, the following research aim is achieved.

*Assessing, in the set-up of the investigated pilot, whether EVs, in combination with blockchain technology, are suitable to provide aFRR and, if so, proposing an integrated solution for the future.*

The research aim is achieved by integrating the distillations of the insights retrieved by answering different sub questions. This section starts with describing the answers of the different sub questions. Subsequently, the overarching research aim is considered.

### 7.1. Answering sub questions

#### 1. *Is the utilisation of EVs for aFRR provision technically feasible?*

Sub question 1 is in particular analysed in Part II. The data analyses provide insights in multiple aspects regarding the technical feasibility of EVs providing aFRR. Inherent to a pilot quite some foreseeable and unforeseeable practical difficulties are encountered. This resulted in situations in which EVs did not provide aFRR as demanded, because of various reasons. For instance, activated EVs that did not respond at all, resumed the original charging behaviour earlier than demanded or did not resume the original charging behaviour after deactivation due to amongst others technical issues and unexpected plugging out .

However, lessons that were deducted from the data analyses were often applied quite rapidly. This has led to immediate improvements regarding the quality of aFRR provision. The data analyses have shown numerous activated bids in which the setpoints were followed as demanded by all activated EVs. More specifically, bids in which i) the regulation rate was higher than minimally demanded and ii) in which a change in power output was observed within the maximum amount of time (i.e., 30 seconds) after receiving a change in setpoints, which is in line with the requirements defined in [8]. Hence, it can be concluded that, according to the data in the pilot, it is technically feasible to provide aFRR by the utilisation of EVs. The thesis also shows that, considering average current charging profiles, many EVs are needed to scale up the available volume for aFRR provision.

#### 2. *What is the added value of blockchain technology for the utilisation of EVs for aFRR?*

Chapter 3 provides insights in the general functioning and value of blockchain technology. In Chapter 4, the investigated application of blockchain is described on a more detailed level. It should be considered that the current application of blockchain technology in the investigated pilot is designed as a minimum viable product. This results in a significant discrepancy between the added value in the investigated pilot and the potential added

value for future solutions. The question is therefore approached from both the current perspective as the future potential one.

In the investigated pilot, the added value of blockchain technology seems relatively low. This is mainly due to the fact that key features of blockchain technology are lacking. For instance, there is no consensus model yet in play. The idea of a consensus model entails that agreement is reached by the network on how the ledger should be updated in order to guarantee data integrity. Without such a consensus model, the ledger is simply updated by the entity that logs new data (e.g., the BSP by logging power outputs or the TSO by logging setpoints). Apart from mechanisms that check general aspects regarding the format of logged information, the current blockchain solution does not seem to result in a higher integrity regarding the input of the data than other technologies do. In addition, no smart contracts are yet enabled. This feature could offer potential advantages regarding the automation of various processes such as the verification and settlement procedures on which is elaborated below sub question 3.

However, some advantages compared to the traditional situation can already be identified. No expensive leased lines have to be constructed to provide a reliable communication channel. More generally, the decentralised character of blockchain technology matches the transformation towards a more decentralised landscape of aFRR provision by a higher number of BSPs. However, this is not a unique advantage offered by blockchain technology and could also be effectuated by other technologies. Another advantage, that is more blockchain specific, is data immutability. Also in the current application, data cannot be changed after it is logged on the blockchain. This prevents potential data manipulation afterwards. However, this advantage would be more valuable if the integrity of the data that is logged on the blockchain would also be ensured.

It is easier to picture the advantages of blockchain technology for a future application in which more parties are involved than only the TSO and one BSP. With a higher number of BSPs the administrative processes for TenneT can be expected to become increasingly difficult and demanding. Especially if the TSO has to process and verify all data internally. Blockchain technology could reduce the burden on the TSO regarding the verification and settlement processes. Smart contracts can help in the automation of for instance settlement processes. Smart contracts are automatically executed predefined agreements (e.g., the financial reward of BSPs is automatically calculated by multiplying the provided aFRR volume with the imbalance price and is also settled automatically).

Blockchain technology could also add significant value in increasing (input) data integrity. With a higher number of assets, the difficulty to verify data integrity by means of physical audits also increases. The proposed method in Chapter 6, in which transactions are always logged by two independent parties, increases the reliability of the input data. This only works, if a functioning consensus model is in play, as it needs to be validated whether the two data logs are consistent.

Lastly, blockchain technology could offer added value in the case of incorporating more and different stakeholders. For instance, DSOs could be incorporated to make predefined transparent agreements regarding congestion management purposes and article 182 [16].

In addition, the technology could also play a role in case of any disputes between BRPs and BSPs connected to the same asset(s). The answers on sub question 3 elaborate on these aspects.

3. *What are possible improvements with respect to the investigated pilot and is it possible to expand the concept for other purposes?*

This question can be answered for multiple aspects of the investigated pilot. Therefore, the answers are structured based on these different aspects.

*Asset level*

The analyses in this thesis show that a vast number of EVs in the fleet is needed per MW provision of aFRR. Besides, the largest share of EVs that are charged at home, are charged in the evening (roughly between 6 – 9 p.m.) and just a small share is charged at day time (roughly between 7 a.m.- 5 p.m.). Considering the fact that the average activated aFRR volume of the last years is highest in the morning (i.e., 7-8 a.m.) it is recommended to add EVs that charge during these ISPs and thus have complementary charging profiles. This could be realised by adding EVs to the fleet that charge at work. Evidently, the fleet size could be increased by adding other types of EVs. Lastly, the option for customers to indicate the desired SoC instead of standardly charging it up to 100% SoC is considered as an improvement, as it could increase the number of ISPs in which EVs are available for aFRR. Besides, it is beneficial in terms of battery degradation [58].

*Shared data*

Regarding the shared data in the investigated pilot, it is assessed whether all shared data is necessary in order to verify whether aFRR was provided as demanded. In particular, sending four reference signals (+1 minute, +2 minutes, +5 minutes and +10 minutes) every four seconds seems somewhat redundant. Especially, because the data analyses show that the quality of the reference signal is (yet) insufficient. Ideally, almost no data should be necessary outside ISPs of activated bids. Perhaps only data just before and just after an ISP should be logged in order to monitor a correct reaction. In the current phase of the investigated pilot, the data outside ISPs in which bids are activated, provide valuable insights. However, when verification processes function reliable, the data outside these particular ISPs should be obsolete, especially the data on asset level. Decreasing the amount of shared data also reduces the required storage capacity of the blockchain application.

*Internal aFRR procedures*

Regarding internal aFRR procedures, two possible improvements are identified. The first one is a rather incremental and minor improvement. As the analyses in Section 2.3.1 show, the minimum required regulation rate of 7% should be higher for smaller bids (up to 10 MW) or the resolution of sending setpoints should be increased (e.g., from integers to decimals) to reach full activation within 15 minutes. The second proposed improvement has a more fundamental character. Instead of verifying aFRR provision based on the difference between the reference signal and the actual power output, it is suggested to purely base this on the actual power output. Or more specifically, the change in power output due to

aFRR activation as described in Chapter 5. In this way the verification of aFRR provision is automated, less data needs to be exchanged and the quality of the verification process does not depend on the accuracy of the reference signal.

### *Blockchain*

Regarding the used blockchain technology, important improvements can be achieved. This is already partially assessed below sub question 2. These improvements relate to integrating key features of blockchain. More specifically the integration of smart contracts is essential to integrate automation which could make the verification and settlement processes much more efficient in the future. Besides, the implementation of a consensus model, that can be a relatively lightweight option as described in Section 6.1, results in an increase in data integrity as well as in decentralised verification.

### *Expand concept for other purposes*

It should be taken into account that deploying decentralised assets for aFRR provision also influences other parties than the TSO and BSPs (e.g., the DSOs and BRPs). The suggested blockchain concept takes the incorporation of these two relevant stakeholders into account. This incorporation results in a solution on a system level. The DSOs are incorporated to support the TSO to comply with article 182 as described in Section 6.2. This article states that DSOs “shall have the right, in cooperation with the TSO, to set, before the activation of reserves, temporary limits to the delivery of active power reserves located in its distribution system” [16]. Incorporating the DSOs in the blockchain concept gives the opportunity to make transparent predefined agreements on how to decide a priori in which situations assets should be deployed for national balancing purposes or for local congestion management. Additionally, the BRPs that have aFRR providing assets in their portfolio that are aggregated by other BSPs could be integrated in the blockchain concept. In this way, the concept provides a transparent method to solve any disputes regarding the actual aFRR provision. Hereby, the TSO complies with one of its legal tasks; facilitating stable and efficient electricity markets [19].

Overall, this research shows that EVs in the combination with blockchain technology can be suitable to provide aFRR. However, it also shows that scaling up while only using EVs that charge at home, requires a vast number of EVs. The thesis suggests multiple potential solutions to this challenge. The research also shows that using blockchain technology results in some added value, but that the real distinctive added value of the technology is not yet realised.

This thesis suggests an integrated methodological guide for the utilisation of decentralised assets and blockchain for grid balancing. More specifically, an alternative aFRR verification and a blockchain architecture are proposed with several potential improvements such as, increased transparency, less time consuming verification processes, increased data integrity and more efficient data exchange, which are all needed in case the concept is scaled up. The proposed solution also considers other relevant stakeholders that are affected by the deployment of EVs (and potential other decentralised assets) such as DSOs and BRPs.

## 8. Discussion

The last chapter of this thesis is a reflection of the quality and the results of the research. It describes the identified limitations of this thesis and it connects these to suggestions for the direction of further research. Lastly, both the societal and scientific implications of this work are described.

### 8.1. Limitations and further research

Several limitations can be identified within this research. This mainly concerns scope related limitations, but also data related limitations.

To start with the latter, the data from the investigated pilot, that is used to assess the feasibility of EVs for the provision of aFRR is rather limited. This applies to both the fleet size and the timespan. The timespan does not exceed a couple of months, whereas the fleet of EVs is not yet large enough to reach the actual minimum bid size of 1 MW. Therefore, one should be careful with generalising the results. However, as the data analyses show accurate individual responses of the EVs to aFRR setpoints, there do not seem to be any evident reasons why EVs would not be suitable assets when a higher number of assets is deployed. Future research in which larger datasets can be used, could reduce the uncertainty regarding this aspect.

There are several limitations that have a scope related character. For instance, the current blockchain concept and the proposed future one are only compared to the existing situation. Hence, no other (new) technologies are analysed and included in the comparison. Further research could include other ICT options that have a decentralised character (e.g., a web service) in order to make a more comprehensive comparison that is not only based on the differences with the current system technologies but also with other alternatives.

Another scope related aspect is the fact that the comparison between the current situation, the current blockchain concept and proposed future concept does not include a financial dimension. No cost assessment is conducted, partially due to confidentiality of data. Besides, no energy consumption assessment is conducted. As described in Section 3.2.1., the energy consumption of Bitcoin and other public blockchain technologies with a PoW consensus model is exorbitantly high. However, it could be assumed that due to the permissioned character of the blockchain technology in the investigated pilot in combination with the lightweight consensus model in the proposed concept that the energy consumption will not result in major issues. Future research could take these financial and energetic dimensions into account.

The last limitations apply to the proposed concept. Firstly, the proposed method of verifying aFRR is not assessed quantitatively. This could be solved by incorporating the method in a potential later expansion of the pilot. Secondly, the transactions in the proposed concept are applicable to EVs and specifically to EVs that are directly connected to a smart meter. Increasing input data integrity, works very well due to the two-way data logging of both the EV and CP. For other technologies such as home batteries or electric boilers other solutions should be applied as they are often not directly connected to a smart meter. Possibilities could lay in the combination of the asset itself, with for instance a home management system with a smart meter. Other possibilities could lay in ensuring the data is logged one

way, but by a comptable<sup>12</sup> meter (e.g., a smart meter). When this condition is met, the proposed concept can easily be expanded for other technologies as well. Thirdly, the option to incorporate other relevant stakeholders in the proposed blockchain concept in the future, such as the DSOs and BRPs, is not discussed with delegates from those parties. This is partially due to time constraints and partially due to confidentiality of the data. However, future research could focus on this topic to assess whether enough support can be created to realise such a solution.

## 8.2. Implications

Despite the various limitations, the thesis has valuable implications. In this thesis, three different research topics and their interaction are analysed. Consequently, implications are found for each topic.

Regarding the suitability of EVs for balancing purposes, it is shown, based on data from practice, that EVs have the technical characteristics to meet the requirements for aFRR provision. Regarding some characteristics (e.g., regulation rate) EVs are even more suitable assets than conventional power plants. However, the research also shows that it will be quite challenging to scale-up the investigated concept rapidly regarding available aFRR power. This is caused by two main reasons. The average travelling distance per day in the Netherlands is quite low. Ergo, the average energy consumption when charging is also relatively small. A smaller energy consumption results in less energy that can be shifted in time and therefore in less ISPs in which aFRR can be provided per asset. In addition, the average residential EV charging profiles show low charging demand during the morning and afternoon. In the thesis is shown that the average activated upward aFRR volume is currently highest in the morning. This implicates that in order to increase the available volume for aFRR provision, the deployment of EVs with complementary charging profiles (e.g., EVs that charge at work) and other assets should be considered. In this thesis, V2G applications are not taken into account. In future applications, this could increase the possibilities regarding bidirectional aFRR provision. It should be emphasised that the proposed concepts can also be deployed for V2G application.

Regarding electricity markets and more specifically aFRR, current patterns and processes are analysed. As mentioned before, the trends of activated upward aFRR volume show the need for decentralised assets with complementary demand profiles compared to residential charging. Regarding processes, the focus in the thesis is on the verification and settlement phase of aFRR provision. The current verification method with the visual analysis of the relation between the reference signal, delta setpoints and the actual power output is assessed. In the light of the features that blockchain technology has to offer, a different method is suggested. This new method reduces the burden on the TSO with respect to verification and settlement procedures, because of automation. In addition, it increases the accuracy and reliability regarding the verification of aFRR provision as it is, contrary to the current method, solely based on actual measurements.

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<sup>12</sup> A comptable meter (in Dutch ‘een comptabele meter’) is a meter that officially can be deployed for the calculation of provided services.

Regarding blockchain technology, the added value for the investigated application is assessed. The thesis shows that the current blockchain concept offers some added value compared to the current situation as it eliminates the need for leased lines and ensures more transparency and data immutability. However, improvements are identified and proposed. The importance of the incorporation of a consensus model and smart contracts is underlined in order to increase (input) data integrity and the efficiency of administrative processes. In addition, it is proposed to incorporate two-way data logging instead of one-way, which would also increase the data integrity. The thesis also touches upon future developments regarding alignment between the TSO and the DSOs (e.g., article 182 [16]) and between BSPs and BRPs connected to the same (reserve providing) assets. The proposed concept in this thesis could contribute to (partially) solving these issues.

Lastly, a more philosophical implication regarding the future role of a TSO can be derived. It should be considered that the TSO betakes itself in an area of fascinating contradictions by exploring the opportunities regarding blockchain technology. On one hand it offers the potential to increase the efficiency and transparency of various administrative processes. On the other hand, the idea behind blockchain technology could subvert one of the core components of the *raison d'être* of a TSO. This does not apply to the task regarding the maintenance and construction of physical assets, but merely to the administrative counterpart. For instance, in the traditional system, the TSO plays the role of a centralised party that is authorised to process and to verify data streams regarding imbalance settlement. The idea that a central authority that is solely in control of all data is needed to create trust, is exactly the way of thinking blockchain technology is meant to overthrow. In this light, I believe that the search of a TSO, or any central authority in general, for the opportunities of decentralisation via blockchain technology, results in an existential paradox. Note that this does not imply that this search is dissuaded, but it only states the potential presence of opposing interests on a higher level.

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