Potential of Smart Charging and V2G

ALIGHT
SUSTAINABLE AVIATION

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The H2020 funded project - ALIGHT – is a Lighthouse project for the introduction of sustainable aviation solutions for the future. The two main topics of the project are A) the supply, integration, implementation and use of sustainable aviation fuel (SAF) and B) the supply, integration, implementation and use of smart energy. This whitepaper describes solutions for workstream B – Smart Energy.

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Executive Summary

Copenhagen Airport (CPH), the Technical Institute (TI), and Hybrid Greentech (HG) have released this report to share insights on how intelligent charge management of Vehicle-to-Grid (V2G), fast chargers, and destination chargers in parking facilities can reduce CO2 emissions and electricity costs. The report outlines what airports or parking facility owners and infrastructure managers need to know to understand the commercial potential and how to harness flexibility.

The Alight project at Copenhagen Airports (CPH) aims to demonstrate realistic integration of smart charging and vehicle-to-grid (V2G) technologies with existing infrastructures. As Scandinavia's largest airport, CPH offers nearly 14,500 parking spaces, with 1.5 million cars parked in the airport in 2018. On average, around 5,000 cars are parked daily, with an increasing number being electric vehicles (EVs). CPH aims to electrify a large fleet of heavy-duty vehicles such as de-icing machines, snowplows, buses, etc., by 2030. In 2022, CPH ordered the first 1,350 electric vehicle chargers, including a mix of fast chargers and destination chargers.

Electrifying infrequently used large vehicles is costly, but by connecting them to Vehicle-to-Grid (V2G) chargers, they can function as batteries, reducing the payback period for the investment to only a few years. With the planned electrification of all their vehicles, CPH could quickly become Denmark's largest battery capacity owner.

The project utilises smart charging and V2G as electrical flexibility assets, contributing to reducing carbon emissions, supporting low-emission mobility, and enhancing grid flexibility for renewable energy integration. By pooling EV flexibility with a battery energy storage system, the project aims to demonstrate combined portfolio control, providing asset owners with vital information for establishing EV charging infrastructure at large parking facilities like CPH.

This white paper demonstrates that shifting EV charging to hours with the lowest electricity prices or CO_2-intensity, can directly contribute to reducing both carbon emissions and electricity expenses. It also highlights the simple implementation of smart charging that can be achieved by adjusting charging power during different pricing periods. Moreover, the paper also addresses value creation through information exchange. It discusses that if the plug-out time and energy demand of EVs can be forecasted at the plug-in time, the charge controller can optimize charging schedules to align with the lowest electricity prices which can lead to increased value and cost savings.

Furthermore, revenue generation through ancillary services is also addressed in the paper. The charge-controller can create an additional revenue stream by selling the power capacity of EV chargers to the transmission system operator (TSO) as ancillary services. These flexible power capacities can be activated to help maintain the power balance in the grid, providing services such as Frequency Containment Reserves for Normal Operation (FCR-N) and Frequency Containment Reserves for Disturbances (FCR-D). It is found that FCR-D offers higher revenue with less inconvenience to EV owners compared to FCR-N, and pooling EVs with a fast asset like a stationary battery can enhance response times.

The white paper provides recommendations for technical implementation, relevant roles, optimal ownership structure for chargers, and market interactions with electricity suppliers, balance responsible parties, and the TSO. It suggests, among other things, that owning the charger provides freedom to utilize flexibility, purchasing chargers with Open Charge Point Protocol (OCPP) communication and a fast-responding back-end operator.

It is concluded that charging flexibility can contribute to reduction of CO_2 emissions, electricity costs of EV charging and grid connection costs. Charging flexibility has shown a potential for reduction of the grid connection costs via peak shaving. Forecasting plug-out time and energy demand allows for further value creation. It is also concluded that provision of ancillary services is the superior choice for increasing revenue streams and providing grid flexibility while having minimal effect on the charging experience. Destination chargers that are in use for minimum 2 hours per day can generate an availability payment of 250-350 € per charger per year by delivering FCR-D, while a well-utilized fast charger could earn around 2,500 € per year.

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Definitions

AC	Alternating Current
ACER	Agency for the Cooperation of Energy Regulators
aFRR	automatic Frequency Restoration Reserves
BESS	Battery Energy Storage System
BMS	Battery Management System (part of the battery system onboard an EV)
BRP	Balance Responsible Party
BSP	Balancing Service Provider, is directly selling the service to an operator
CP	Control Pilot
CPH	Copenhagen Airports
CPO	Charge Point Operator, controls a charge asset
DC	Direct Current
DER	Distributed Energy Resources
DK1	Bidding zone in the western part of Denmark
DK2	Bidding zone in the eastern part of Denmark
DSO	Distribution System Operator
EAM	Energy Activation Market
ESM	Electricity Storage Module
EV	Electric Vehicle
EVSE	Electric vehicle supply equipment
FCR	Frequency Containment Reserve
FCR D	FCR for disturbances
FCR N	FCR for Normal Operation
FFR	Fast Frequency Reserves
LFSM-O	Limited frequency sensitive mode at over frequency
LFSM-U	Limited frequency sensitive mode at under frequency
mFRR	Manual Frequency Restoration Reserves
MSP	Mobility Service Provider
NEMO	European Nominated Electricity Market Operator
NRA	National Regulatory Authority
OCPI	Open Charge Point Interface
OCPP	Open Charge Point Protocol
OEM	Original equipment manufacturer
OSCP	Open Smart Charging Protocol

PV	Photovoltaic system
PWM	Pulse Width Modulation
RES	Renewable Energy Sources
RGCE	Regional Group Continental Europe
RGN	Regional Group Nordic
RTE	Round trip efficiency
SOC	State of Charge (SOC): Stored energy in the battery in percent of the useable capacity.
TSO	Transmission System Operator
V2G	Vehicle-2-Grid

Preamble: Parking in Copenhagen Airports

Copenhagen airports (CPH) offers reservation options for nearly 14,500 parking spaces. In 2018, 1.5 million cars parked at the airport. The average number of parked cars are 4,000 to 5,000 around the clock. All cars will eventually be electric vehicles (EV)s, but it is uncertain how many EVs will need charging while parked, as the parking times vary from minutes to days.

Table *1* shows the current distribution of parking sessions with different durations at CPH parking spaces of which most are without chargers. 39% of parking sessions are short-term parking between 0.5-2 hours, which is enough for a meaningful charging session covering most daily demands with a slow charger, and at the same time short enough that the parking time does not exceed the charging time; and thus, yielding a high utilisation of the charge point. The parking time does however need to exceed the needed charging time before it is possible to utilise the flexibility of postponing the charging.

There is a similar share of 34% of cars that are in long-term parking for more than 24 hours. Those cars have a very high flexibility for scheduling the charging, as it can often be postponed for several days. An EV only needs to charge one hour to cover an average daily driving consumption and maximum six hours if it is a long-range model that arrives with a low SOC. Multi-day parking therefore results in very low utilisation rate of the connected charger, which also results in low average flexibility per charger. For those parking spaces it would be ideal to use vehicle-to-grid (V2G) chargers that are able to both charge and discharge the EV, thereby making it a resource throughout the entire stay.

Table 1 *Distribution of parking sessions with different durations at CPH parking houses*

Parked time	Distribution
1-30 minutes	16%
31 minutes - 2 hours	39%
2 hours - 24 hours	11%
More than 24 hours	34%

Expanding the airport's electric infrastructure to also supply parked vehicles, taxis, Ground Support Equipment (GSE) and maybe future electric airplanes is an infrastructural challenge, but the peak demand can be reduced using smart charging in combination with battery energy storage systems and even available V2G chargers.

1 Overview

This section serves as an overview of the report's content. Firstly, the topic of electric vehicle charging is introduced in Section 2. Secondly, the value of different options for flexible operations via electric vehicle charging is estimated in Section 3, which is followed by a case study in Section 4 to show the value of the most prominent EV flexibility values – provision of ancillary services at Copenhagen Airport. Lastly, Section 5 presents the roles and responsibilities of the main actors in implementing flexibility services with EVs.

2 Electric Vehicle Charging

The key to EV charge management is the EV chargers. An EV charger is a device that enables the supply of power from the electric grid to charge the battery in an EV or plug-in hybrid. For the charger there is no difference between an EV and a plug-in hybrid. There are different types of chargers for different vehicle types and required charging power. Some chargers can be controlled remotely, and some cannot.

Charging can be classified using 3 categories:

- **Charging type**: AC or DC – some EVs only accept AC power but most EVs can accept both AC and DC. It is describing the type of power passing through the cable to the EV.
- **Charging mode**: Characterised depending on the power delivery, control of charging system and protection installation.
- **Charging level**: Characterised depending on the maximum capacity of power delivery possible through the cable and the charger.

The charger can have various cables and connectors for the charger. However, the EU encourages IEC 61851 standard charger connectors for AC chargers and Combined Charging System (CCS - ISO 15118) for DC chargers. Even though these are already dominating, a few DC chargers with the Japanese CHAdeMO standard connectors are still around, and some Tesla chargers may still have proprietary Tesla connectors.

EU is also trying to harmonize terms that can be used to describe the nature of the EV charging connection to the grid. New relevant definitions proposed in context of European Union Agency for the Cooperation of Energy Regulators (ACER) is expected to be used in future for simple indication of uni- or bi-directional type and power level. The new terms include:

- **'V1G electric vehicle'** means an EV that is powered with electricity and can only consume electricity from the grid.

- **'V2G electric vehicle'** means an EV that is powered with electricity and is equipped with technology enabling the vehicle to deliver electricity back to the grid.

V2G type “**EV1**”: 0,8 kW ≤ capacity < 2,4 kW

V2G type “**EV2**”: 2,4 kW ≤ capacity < 42 kW

V2G type “**EV3**”: 42 kW ≤ capacity < 1 MW

V2G with larger capacity than 1 MW is considered an **Electricity Storage Module** (**ESM**)

- **'Electric vehicle charging point or installation'** means the infrastructure necessary to safely conduct electrical energy between the electricity supply grid and the electric vehicle. Domestic electrical wirings are not deemed part of an EV charging point or installation.

- **‘Electrical charging park’** means the installation that has a single connection point to the relevant network (electric grid) and where one or more EVs can be simultaneously connected.

After this introduction to overall terms, it is time to look a bit closer into the inner workings of chargers to identify the limited control options available for smart management.

2.1 Charging Destination Types:

The public charge points at CPH can be divided in two categories:

- **Charging Destination**: These are charge points that are dedicated locations for EV charging. Hence these locations need to have high power chargers installed.
- **Destination Charging**: This is where EV owner would go regardless of the charger such as parking lots of offices, shopping centres, sports stadiums, etc. Having the charger installed in the location will be an added value for the EV owner as it helps them to cover their public charging demand. Destination charging generally consist of AC chargers rated to 11 kW or 22 kW.

CPH primarily has a need for destination chargers, because users travel to the airport regardless of the chargers. Fast chargers can be used in spaces of short period parking and slow chargers can be used in the long period parking spaces.

2.2 Charging Types

2.2.1 AC Chargers

AC charging is the default charging option for all EVs as access to AC charging can be established everywhere with access to the electricity grid. The figure below shows a simple EV charging architecture for an AC charging setup. An EV battery can be only charged using DC supply, hence in AC charging, an on-board charger converts the AC supply from the grid into DC and charges the battery. Therefore, the charging rate is limited by the capacity of the on-board charger. An AC charger is commonly referred to as an Electric Vehicle Supply Equipment (EVSE), to differentiate the fixed installation from the on-board charger.

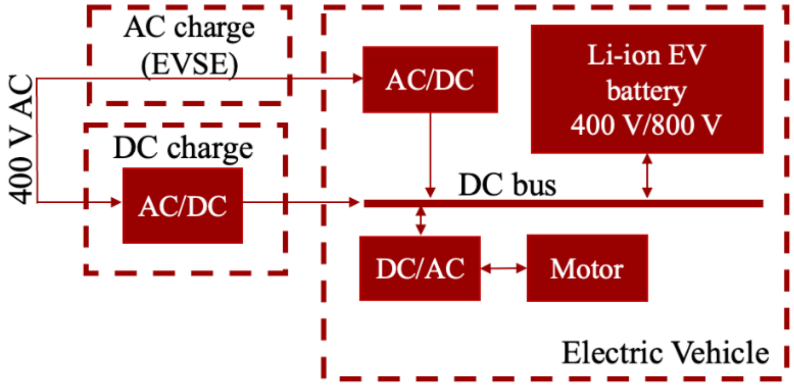


Figure 1 *Illustration of essential charging components in an EV. For AC charging the AC to DC converter is part of the vehicle. The EV battery system can always limit the charge current as well as the EVSE can allow a maximum current through the charge cable.*

The EVSE for AC charging is essentially an electric socket for the AC-grid with added signalling for safely managing the EV charging. There is no conversion of the AC voltage in an AC charge point.

Figure 2 *A wall full of different EVSEs on display at the site of charging settlement back-end operator, Monta, illustrating differences in mechanical design of the box, but all with same basic functionality. There can be small variations between boxes in the level of remote charge control available [1]*

AC charge points are unable to identify the EV and the State of Charge (SOC) from the vehicle. The charge point controls have not yet implemented the complex communication integrated into DC-chargers, and many EVs do not support high level communication for AC-charge only.

The on-board AC-charger may have a bi-directional option in the future, such that V2G could be delivered from the vehicle through the charge port. Several vehicles already offer AC-outlets in the vehicle for auxiliary purpose, and a couple of vehicles are ready to offer V2G AC-power through the charge port. There are regulatory issues with feeding power into the grid that need to be sorted first. The Danish Technical Regulation 3.3.1 covering grid connected electric energy storage systems includes V2G on equal terms of other types of grid-connected energy storage.

EVs have different charging current capabilities. Therefore, the AC Charger must communicate the maximum available current capacity to the EV, such that it can respect the limit. The EV and EVSE execute a handshake before the charging process can start via the communication pin, known as the Control Pilot (CP), shown in **Figure *3***.

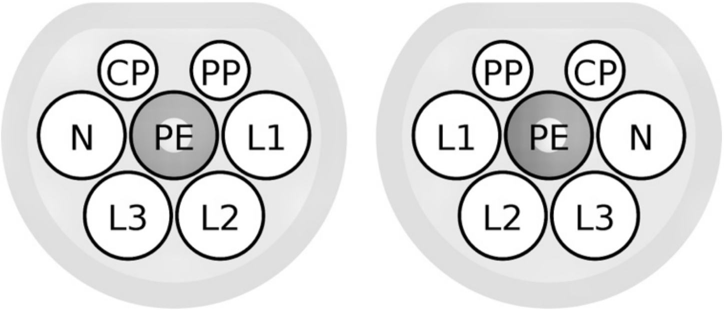


Figure 3 *Left: AC cable Type 2 connector (Female), Right: AC vehicle Type 2 inlet (Male)*

Figure *3* shows the standard AC charging plug, it is known as the Type 2 plug in the IEC 61851 standard. The Type 2 plug contains three-phase power pins (L1, L2 and L3), a neutral pin (N), protective earth (PE), as in a normal AC cable, but two more pins are added for handshake and communication: proximity pilot (PP) also used for cable identification; and a control pilot (CP) pin for communication with the EV through +/-12 V PWM signals.

The PP pins are only connected locally inside the connector with a resistor to the earth-pin. The resistor value signals the ampere rating of the cable (1500 ohm: 13 A; 680 ohm: 20 A; 220 ohm: 32 A; 100 ohm: 63 A).

By default, the EVSE generates a 12 V signal on the CP. When an EV is connecting, it is reducing the voltage to 9 V via a resistor in the EV. The voltage drop is a part of the handshake signalling that the EV is ready to charge. After this, the EVSE will send a PWM signal with a duty cycle value corresponding to the current rating, as shown in **Figure *4***.

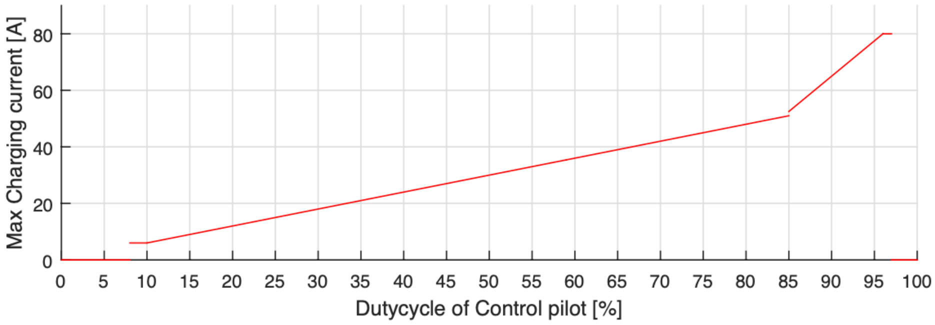


Figure 4 *Duty cycle of the PWM signal of the control pilot and maximum charging current it represents as described in the IEC 62196 standard*

The EV will consume a current equal to or lower than the limit informed from the EVSE, but first it performs the final handshake by dropping the PWM voltage to 6 V after which the EVSE connects the relay, and the charging begins.

2.2.2 **DC Chargers:**

A DC charger is made with the AC to DC conversion inside the EVSE and outside the EV. The DC charger bypasses the on-board charger and charges the EV battery directly under the supervision of the Battery Management System (BMS).

A DC EVSE generally has less weight and space restrictions and can supply more power. Hence, DC chargers are also referred to as fast chargers. There are basically three different DC power ranges available: 50 kW DC chargers were the first available and has the lowest installation cost – these are considered "normal" DC chargers. EVSE with DC power ranges between 50 kW and 150 kW are called fast chargers. For power ranges above 150 kW (up to currently 350kW), chargers are referred to as ultrafast chargers.

The EVSE communication with the BMS demands a more high-level communication to ensure safe and secure charging. The cable for fast charging is always installed on the DC EVSE. The cable needed for ultrafast charging must have a very large cross section to avoid overheating during high power charging.

The charging of an EV is always controlled and limited by the BMS in the vehicle battery. The charge point offers a maximum power or current available to the vehicle. Some of the pilot pins in the connector used for AC-charge control doubles with multiple functions during DC-charge as shown in **Figure *5***.

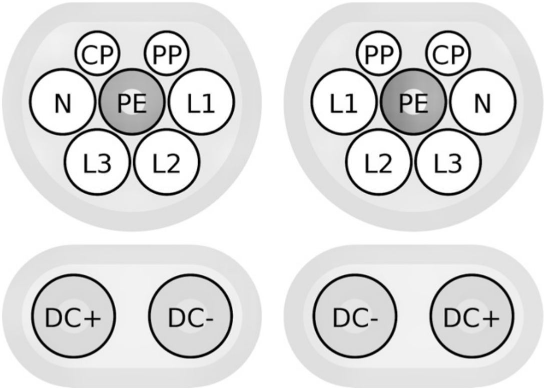


Figure 5 *Left: DC cable CCS connector (Female), Right: DC vehicle CCS inlet (Male)*

2.3 How Can AC & DC Chargers Be Controlled?

The Charge Point Operator (CPO) uses the back-end system to manage charge points via high level communication protocols – typically over the internet. The management include customer identification for charge authorization and payment. One charge point operator often needs to manage multiple charge points of different brands and types (e.g. a mix of AC and

DC fast-chargers). Usually, they can use the same communication protocol for all charge points via OCPP.

The Open Charge Point Protocol (OCPP) from the Open Charge Association has developed into a de facto industrial standard protocol for most producers of charging equipment. OCPP has become the global open communication protocol between charge points and the back-end systems of CPOs. OCPP 2.0.1 is the latest Open Charge Alliance protocol offering plug-and-charge and smart charging requirements along with V2G support.

2.3.1 **OSCP**

Open Smart Charging Protocol (OSCP) is an open communication protocol between a charge point management system and an energy management system. This protocol imparts a 24-hour forecast of the accessible capacity of an electricity grid. Both OCPP and OSCP are maintained by the Open Charge Alliance (OCA), a worldwide consortium of EV infrastructure pioneers that foster open standards in EV charging infrastructure.

2.3.2 **OCPI**

Open Charge Point Interface (OCPI) is an open protocol used for connections between CPOs. Simply put, this protocol facilitates automated roaming for EV drivers across several EV charging networks. This interface underpins the affordability and accessibility of charging infrastructure for the EV owners, allowing drivers to charge on several networks. The protocol provides accurate charge station data such as location, accessibility, and pricing, and it considers real-time billing and mobile access to charge stations. The OCPI protocol is managed and maintained by the EVRoaming Foundation, ensuring its free availability.

2.3.3 **ISO 15118**

ISO 15118 is an international standard that defines a communication protocol between the EV and EVSE. The protocol enables plug & charge capability, wherein authorisation to start charging is triggered simply by connecting a vehicle to a charger. It is recognised as an important contributing factor to accelerate EV adoption, as plug & charge greatly simplifies EV driver’s charging experience. ISO 15118 also enables bi-directional EV charging, otherwise known as V2G. With V2G, EVs will be able to feed energy back to the grid when needed, thus helping reduce costly system peaks.

For EVSE and EVs using OCCP 2.0.1, the vehicle SOC can be accessed, also during AC-charging. Knowing the SOC will allow for more advanced use of the remaining charge capacity in a virtual powerplant or smart energy system. This is because the maximum charge power an EV can accept during a fast charge depends on battery temperature and state of charge. Figure 6 shows a typical charge power characteristic as a function of SOC.

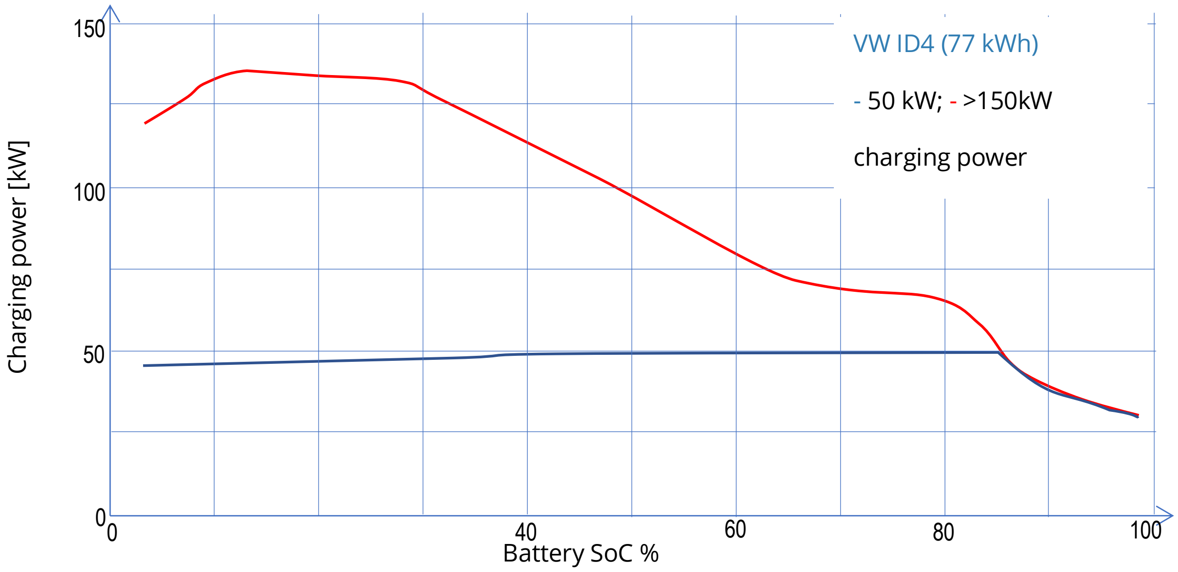


Figure 6 *Example of charging characteristic for a VW ID4, test made by Danish Technological Institute*

For V2G application the restriction on maximum available discharge power may be similar to the challenges under charge.

2.4 Opportunities and Barriers with EV Charging Technologies

The existing EV charging technologies allow for flexible use but there are still technical limits and barriers that need to be considered when evaluating the flexibility potential.

The battery itself has natural limitations on energy and power. The available energy for V2G and smart charging is dependent on the battery SOC and can furthermore be restricted by the manufacturer and/or the EV owner to protect the battery or for convenience reasons.

One of the main practical barriers for utilization of more intelligent smart charging and V2G is that most EVSE hardware is not ready, or that the actual firmware version of charging protocols does not support data communication from the EV to the EVSE, which prevents the actual status of available power and energy to be communicated and fully exploited for flexibility. This makes planning more uncertain as the flexibility potential must be based on statistical forecast.

Moreover, the missing control from the EV owner of his/her own vehicle might create unnecessary scepsis, as he/she needs to rely on the charge controller to allow for smart charging or V2G. Even newer charge-hardware may only be compatible with OCPP 1.6 or older versions, which have status as industrial norms. It is not normal practice to upgrade existing chargers with newer protocols, as these might require hardware upgrade to utilize a software upgrade.

Often, the access to control an EVSE is also complicated by a complex responsibility/owner structure, where many parties need to be involved. The roles and responsibilities are further described in Section 5, but some of the dilemmas could for example be:

- The car-producer has no interest in allowing extra wear on the vehicle battery from grid services.
- The car owner might have an interest in accepting extra wear on the vehicle battery if the revenue outweighs the reduced battery life.
- The CPO will only handle the extra work and communication load on their network if it is fully financed. Changes may be needed in the grid connection agreement with the DSO.
- An aggregator may be needed to create a large enough critical mass for selling the service to the grid – this work must be compensated by the service revenue created.
- A balance responsible party is needed to sell the services.

It is also worth noting that the available charging and discharging power can differ from day to day and significantly from summer to winter, and that the power typically will be limited under low temperature conditions. This means that an EV cannot be used directly as a symmetric electric flexibility asset.

The DC charging technology gives the best opportunities for V2G from a technical point of view, as the power electronic hardware is physically located on ground and thereby not limited in size and weight by the EV. However, as an EV using fast charging with a higher power will typically only be connected for immediate charging, DC chargers will be less optimal for V2G scenarios.

The business case of installing V2G chargers depends on cost of hardware and cost-effective access to the grid – and especially regulatory barriers or special taxation for V2G access may stop V2G from developing in Denmark. AC chargers have less regulatory issues with grid access and is therefore the better candidate for smart charging and utilization of flexibility. Using AC charging for smart services e.g., peak shaving and cost/CO_2-optimization, as described in Section 3, is optimal as the EV is typically plugged in for a longer period allowing for the smart management.

V2G technology built into the vehicle's AC charger hardware could give other opportunities for even more flexibility utilization, but it requires up to date EVSE hardware and software to allow for bi-directional power flow, and it may likely be inhibited by barriers put up by original equipment manufacturers (OEM).

3 Flexibility of Electric Vehicle Charging

Flexibility can be divided into different use cases or distinct operations of an EV-charger that can generate economic value. These use cases include:

- Peak shaving
- Electricity costs reduction
- CO_2-emission reductions
- Energy arbitrage
- Delivery of ancillary services

The use cases are based on the Danish system, which consists of two price zones connected to different electrical grids with variety in regulations. The Western part of Denmark (DK1) is connected to the continental European power system and follows the grid code of ENTSO-E Regional Group Continental Europe (RGCE). The eastern part of Denmark (DK2) is connected to the North European Power system and follows the common grid code agreed in ENTSO-E Regional Group Nordic (RGN).

3.1 Peak Shaving

EV charging can be scheduled to avoid short-term congestion, known as peak shaving. Peak shaving can be monetized at different stages by avoiding investments in increased system capacities at the following levels:

- Reducing the needed grid connection and the local installation behind the meter.
- At the local distribution grid, mitigating the bottlenecks of the grid company.

3.1.1 Reducing Cost in Own Installation with Load Sharing

Load sharing is a local control measure that can reduce investment costs by dividing the maximum charging power that the charging infrastructure can deliver between several EVs.

This can be done on an EVSE level:

- A 32 A (22 kW) EVSE with two plugs could be set to reduce the power of each plug to 16 A (11 kW) when two EVs are charging simultaneously, reducing the power delivery but only requiring a cable and fuses that can handle a total load of 22 kW.

And at a charging site level:

- EV chargers can adjust their charging power according to the consumption of other chargers in a group. They are often grouped by up to 8 chargers per 63 A fuse, such that they reduce the charging current to 7 A (4.8 kW) per charger when all chargers are occupied but each able to deliver up to 22 kW, if only two cars are charging.

The utilization of the parking lot is important when designing a load sharing control for multiple chargers. A parking lot with low utilization rate and extended parking durations is an ideal use case for load sharing. A parking lot with high utilization rate, for example a parking lot accommodating taxis or short-term parking cannot implement load sharing without affecting the quality of the service and delivering less than the demand.

3.1.2 **Reducing Cost of Grid Connection Fee and Capacity Payment**

When establishing a new grid connection, customers must pay a significant fee to the distribution system operator (DSO) to ensure that the energy reaches the installation. In addition, many countries have a yearly capacity payment. Load balancing EV charging can reduce the cost of upgrading the grid connection and reduce the cost of the capacity payment by managing the maximum charging power to adapt to the capacity of the connection i.e., transformers, cables, and circuit breakers.

In Denmark, customers of the DSOs are categorized as either A-high/low, B-high/low or C customers, according to their maximum power demand and the required voltage level at the point of connection.

- **A-high** customers are connected in the 50 kV (DK2) – 60 kV (DK1) side of a main station.
- **A-low** customers are connected at the 10 kV side of a main station.
- **B-high** customers are connected in the 10 kV grid.
- **B-low** customers are connected on the 0.4 kV side of a 10/0.4 kV substation.
- **C** customers are connected to the 0.4 kV grid (most households and small businesses).

A grid connection is paid per Ampere for the highest current available on one phase. Connections at higher voltage levels use less of the distribution grid and therefore pay a lower price for the connection, as seen in **Table *2***, which also shows the respective costs for a 11 kW charger with a full connection and with load sharing.

Table 2 *Connection capacity fee in Radius and Cerius area of Denmark per Ampere or per 11 kW charger with and without load sharing [3][4].*

Customer type	Connection fee €/A	Cost per 11 kW charger (16 A)	Cost for charger with load sharing (7 A, 4.8 kW)
B-low (400 V)	162	2.592 €	1.134 €
B-high (10 kV)	157	2.512 €	1.099 €
A-low (10 kV at 60/10 kV st.)	106	1.696 €	742 €
A-high (60 kV)	59	944 €	413 €

Load sharing can reduce the capital investment cost of installing many chargers, since the connection fee for 16 A is larger than the hardware and labour cost of installing a charger.

3.2 Electricity Cost Reduction

For sites that also have local electricity production, from e.g. photovoltaic (PV) plants, it is often the case that they export to the grid in some hours, while there is an import in other hours. It is beneficial to push the charging consumption to the periods with overproduction, and thereby avoid exchanging electricity with the grid. It has economic value and creates a CO_2 reduction for the site.

3.2.1 **Economic Value**

There is a significant difference between the price of the energy imported from the electricity grid and the energy exported to the grid.

The energy imported from the grid is settled with the electricity spot price plus tariffs, while the energy sold to the grid only yields the spot price minus the feed-in tariffs. Therefore, there is value in minimizing the export to the electricity grid by using all produced energy behind the electricity meter. This is called “behind-the-meter optimization".

The value-creation essentially comes from saving tariffs by using all the produced energy directly, instead of selling it to the electricity grid and buying it back later at a higher price.

The cost of electricity consists of these three elements:

- **Electricity price**: Fixed price agreement or variable hourly price. The spot price is determined by the hourly supply and demand.
- **Transmission System Operator (TSO) tariffs**: The tariffs for Energinet are the same for all types of consumers in all hours: 16.51 €/MWh for consumption [6]. The feed-in tariff and balance tariff for production is equal to 0.62 €/MWh.
- **Distribution System Operator (DSO) tariffs**: Time of use tariffs to the local DSO (e.g. Radius) e.g. for a B-low customer: 8.90 €/MWh in low-load periods, 26.70 €/MWh in high-load periods and 53.40 €/MWh in peak-load periods for a B-low customer [3].

Large companies connected at high voltage levels pays a relatively lower share of their electricity bill to tariffs than a household, for example. This also means that the savings achieved from shifting the consumption is lower for industrial customers than households. Residential customers in Denmark also pay an electricity tax of 93.56 €/MWh, as well as value added tax (VAT) on top of the total electricity cost.

The most relevant distribution tariff for flexible consumption is the time-of-use tariffs. From January 1, 2023, the tariff will depend on three daily time periods - low load, high load, and peak load, named after the usual load at that time of day. The tariff is known in advance, which eases the process of shifting demand, since the tariff is always lower at night. For C-customers, primarily households, the distribution tariff will also vary between summer and winter. The DSO tariffs shown in **Table *3*** are the tariffs valid from January 1, 2023.

Table 3 *Radius Elnet DSO Tariffs per MWh for the different customer categories*

Customer type	Low load	High load	Peak load	Feed-in	Availability
C winter (0.4 kV)	22.83 €/MWh	68.50 €/MWh	205.48 €/MWh	0.68 €/MWh	43.34 €/MWh
C summer (0.4 kV)	22.83 €/MWh	34.24 €/MWh	89.03 €/MWh	0.68 €/MWh	43.34 €/MWh
B-low (0.4 kV)	8.90 €/MWh	26.70 €/MWh	53.40 €/MWh	0.68 €/MWh	18.85 €/MWh
B-high (10 kV)	6.16 €/MWh	18.50 €/MWh	36.98 €/MWh	0.68 €/MWh	14.50 €/MWh
A-low (10 kV)	3.60 €/MWh	10.81 €/MWh	21.61 €/MWh	0.35 €/MWh	8.56 €/MWh
A-high (60 kV)	2.30 €/MWh	4.59 €/MWh	9.19 €/MWh	0.13 €/MWh	4.12 €/MWh

The periods for low, high, and peak load for Radius Elnet customers are shown below.

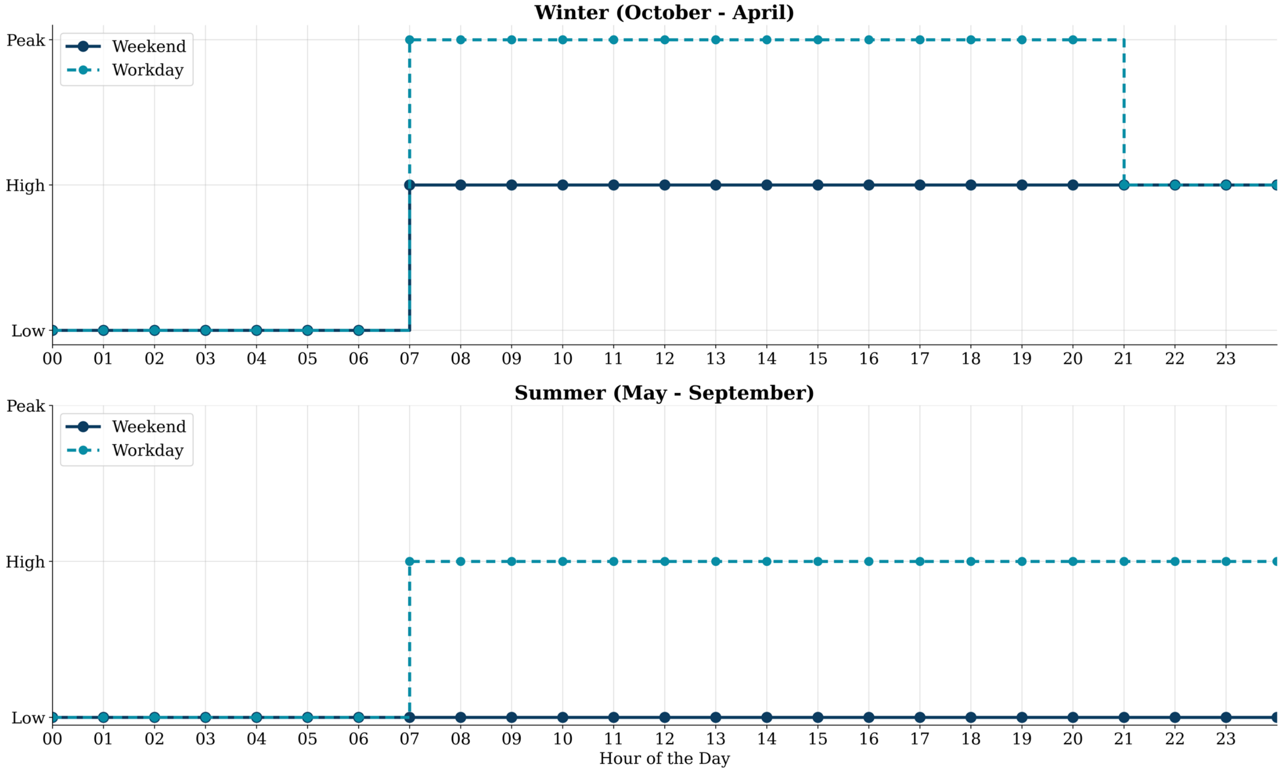


Figure 7 *Radius Elnet low-, high- and peak load periods [3]*

The cost of supplying energy to the grid is only a feed-in tariff of 0.62 €/MWh to the TSO [6] and 0.68 €/MWh to the DSO for a B-low connection.

However, the DSO also requires a fee for the own consumption used directly from the local production behind the meter. The DSO charges an availability tariff of 18.85 €/MWh for B-high for all the production used behind the meter. The availability tariff only applies to self-consumption from local production with a power capacity of 50 kW or above, which is required to have its own energy/billing meter to determine the share of the production that is not exported to the grid. The logic behind the availability tariff is that the network is dimensioned after the peak load and since self-consumption not necessarily result in a lower peak load, prosumers, actors that are both producers and consumers, must pay an availability tariff for the DSO to be available to supply the peak load.

The economic savings for each MWh used behind the meter, as calculated below, depends on the connection type and the load tariff category, which can be found in **Table 4**.

$$\text{Savings per MWh} = \text{TSO Feed-In \& Consumption} + \text{DSO Feed-In \& Consumption} - \text{DSO Availability}$$

***Table 4** Savings per MWh used behind the meter instead of exporting and importing for time-of-use tariffs for the largest customer categories*

	Low load	**High load**	**Peak load**
C winter	-3.10 €/MWh	42.56 €/MWh	179.54 €/MWh
C summer	-3.10 €/MWh	8.31 €/MWh	63.10 €/MWh
B-low	7.46 €/MWh	25.26 €/MWh	51.96 €/MWh
B-high	9.07 €/MWh	21.41 €/MWh	39.89 €/MWh
A-low	12.11 €/MWh	19.32 €/MWh	30.12 €/MWh
A-high	15.03 €/MWh	17.33 €/MWh	21.93 €/MWh

The availability tariff removes a large part of the savings from behind the meter optimization. For small C-customers, it is cheaper to export and import than to self-consume in the low tariff periods. However, C-customers rarely own a >50 kW PV plant, and as such they rarely need to be concerned with availability tariffs.

Consider a case of 100 public EV chargers with a B-low connection, each having an average daily consumption of 150 kWh, amounting to 55 MWh per year per charger.
If 50% of this charging load is within high load hours, 30% within peak hours and 20% within low load hours, the yearly value of behind-the-meter consumption for a fleet of 100 EV chargers would be:

$$55 * \big((16.51 + 0.62 + 0.68 - 18.85) + 0.5 * 26.70 + 0.3 * 53.40 + 0.2 * 8.9\big) * 100 = 165{,}605\ \text{€}$$

3.3 CO_2-emission Savings

Apart from avoiding export of electricity, it is possible to achieve emission savings by importing electricity during the hours with the highest share of renewable generation in the grid, which gives the lowest CO_2 emission intensity. **Figure *8*** shows differences in the CO_2 intensity of the grid on different time scales throughout 2022. More flexibility with respect to how long the consumption can be postponed yields larger emission reductions. A median emission reduction of 55 g/kWh can be achieved if the load can be shifted up to 8 hours.

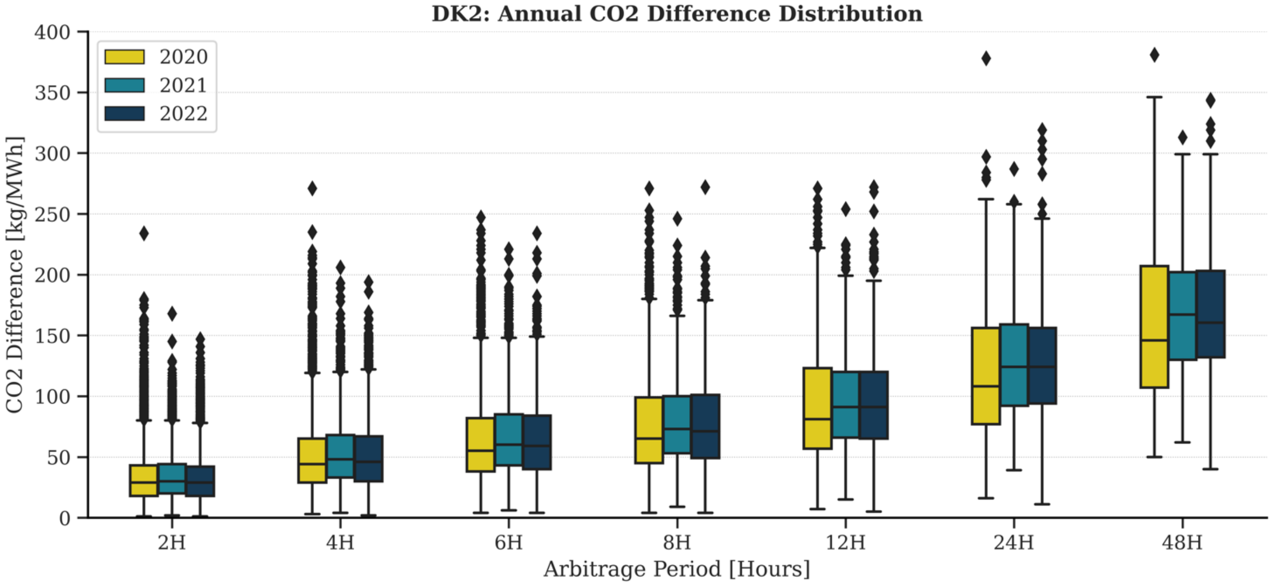


Figure 8 *Box plot of the maximum difference in CO_2 intensity (gr. CO_2/kWh) of the grid for durations of different lengths throughout the years 2020, 2021 and 2022 in DK2*

The CO_2 savings are given as a function of grid intensity by:

$$\mathrm{CO_2\ savings} = \mathrm{Load_{MWh}} * \left(\text{Time-of-Consumption Intensity} - \frac{\text{Import Intensity}}{RTE}\right)$$

Consider a BESS with an RTE of 0.9. By importing 0.8 MWh during an hour with a grid intensity of 40 kg/MWh and consuming it later, where the grid intensity is 150 kg/MWh, the following CO_2 emissions are saved:

$$\mathrm{CO_2\ savings} = 0.8\ \mathrm{MWh} * \left(150\ \mathrm{kg/MWh} - \frac{40\ \mathrm{kg/MWh}}{0.9}\right) = 84.44\ \mathrm{kg}$$

3.4 Energy Arbitrage

Apart from the savings on tariffs from minimizing the usage of the distribution grid, there is also potential for reducing the cost of the energy itself. The price of electricity is settled on an hourly basis in the European Nominated Electricity Market Operator (NEMO) day-ahead auction, which means that the electricity spot price is fixed during the hour but can vary significantly from hour to hour. Earning money on spot prices differences between hours is referred to as energy arbitrage. Most retailers in Denmark offer a spot price agreement, where the final costumer pays the actual hourly spot price plus a retailer fee.

The prices naturally fluctuate during the day, and there is an increasing trend of price differences between morning and afternoon peaks and noon and night-time valleys, as shown in **Figure *9*** for DK1 and **Figure *10*** for DK2.

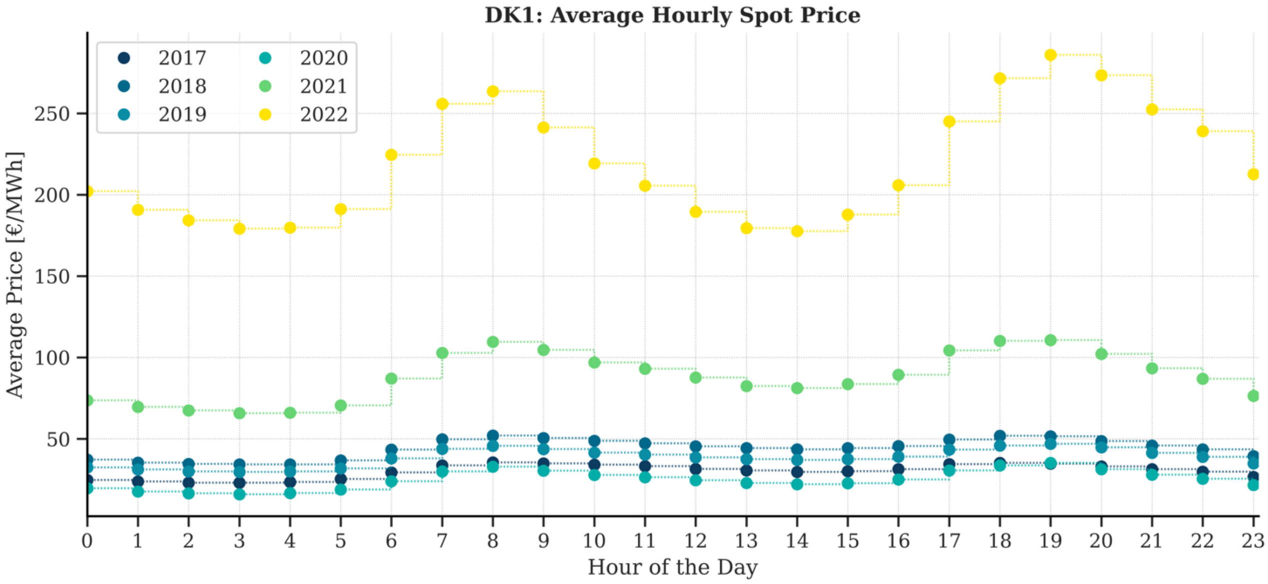


Figure 9 *Daily average price patterns for each year from 2017 to 2022 in DK1*

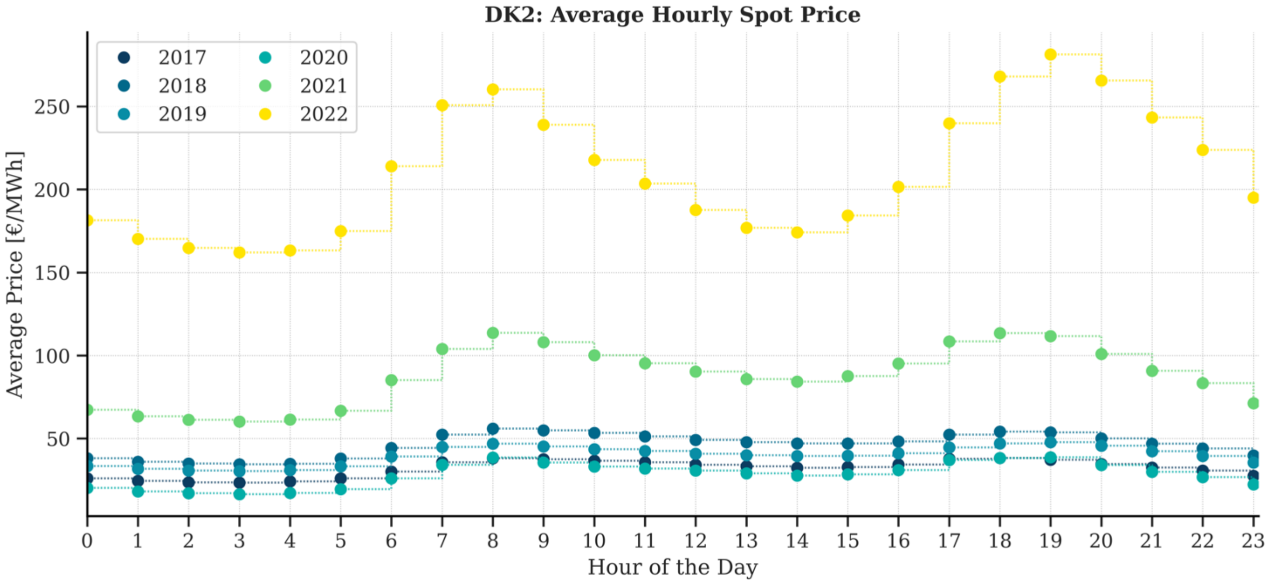


Figure 10 *Daily average price patterns for each year from 2017 to 2022 in DK2*

The value of behind-the-meter optimization can be combined with spot price savings by placing most of the consumption in the hours with lowest prices.

With V2G chargers, it is possible to achieve even higher arbitrage earnings by exporting to the grid, when the prices are high, such that it can import even more, when the prices are low.

Electricity can be sold or bought by being exported or imported to or from the grid. The previously described consumption and feed-in tariffs apply when exchanging energy with the grid, which gives the following buying and selling prices.

The asset will buy and sell energy at the following prices:

$$\text{Import Price} = \text{Spot Price} + \text{TSO Consumption} + \text{DSO Consumption}$$

$$\text{Export Price} = \text{Spot Price} - \text{TSO Feed-In} - \text{DSO Feed-In}$$

The cost of energy conversion losses should also be considered, as the asset has a certain round-trip efficiency (RTE). For an energy transaction to be economically feasible, the difference between the spot price when buying and selling should exceed the cost of tariffs and conversion losses.

The spot prices need to have significant price differences before it is possible to generate a profit from the arbitrage. **Figure *11*** shows the spread of price differences occurring throughout the years of 2020, 2021 and 2022 for different period lengths. It is shown as a boxplot for each period duration. There are generally very limited price differences from one hour to the next with the largest median being only 20 €/MWh. The median price difference increases when looking at longer periods and is above 200 €/MWh for 48 hours based on 2022 prices. DK2 generally experiences higher fluctuations, as it more often has very low prices due to congested interconnectors.

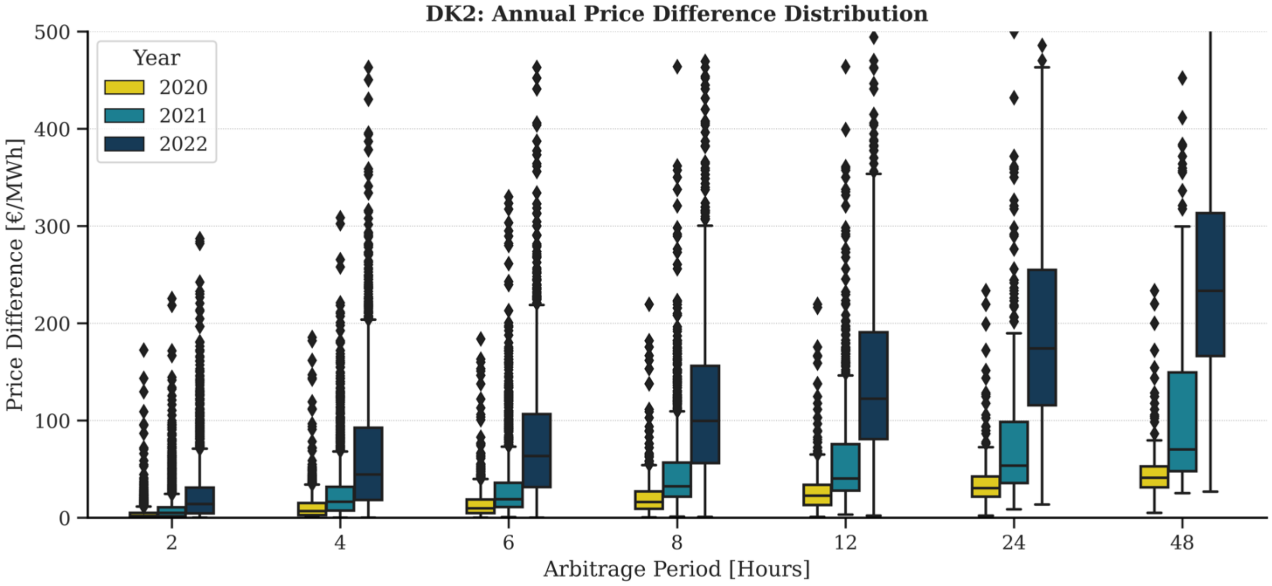


Figure 11 *Spread of price differences occurring throughout the years of 2020, 2021 and 2022 for different period lengths in DK2.*

The price differences can occasionally be significant and by far exceed the cost of exchanging energy with the grid. However, the frequency of these differences is equally important when calculating the yearly value. Assuming it is possible to move 1 MWh every 12 hours to earn 100 €/MWh, the potential revenue would be 73 k€ per year. The spot price fluctuations have, however, only been large in the previous two years, while the prices were very stable in the preceding years.

3.4.1 Value of Energy Arbitrage in DK2

Table *5* shows how much it is possible to earn per year with a directly grid connected battery of 1 MW / 1 MWh (useable) capacity, that only can exchange energy with the grid, and therefore is paying tariffs for every import and export. The results are calculated assuming a charging and discharging efficiency of 90%, resulting in a RTE of 81%. The charging and discharging schedules are determined with a Mixed Integer Linear Programming (MILP) optimisation function that calculates the economically optimal operational profile considering all relevant constraints.

Table 5 *Yearly earnings of a 1 MW / 1 MWh battery operated optimally*

	A-high	A-low	B-high	B-low	C
2017	1.306 €	1.183 €	989 €	860 €	455 €
2018	2.381 €	2.225 €	1.967 €	1.772 €	1.110 €
2019	1.577 €	1.414 €	1.197 €	1.050 €	516 €
2020	3.998 €	3.704 €	3.259 €	2.925 €	1.671 €
2021	14.187 €	13.455 €	12.638 €	12.054 €	9.765 €
2022	45.644 €	43.845 €	41.699 €	40.074 €	34.940 €

Table *6* shows how long it would take to pay back a 1 MW/1 MWh battery with a cost of 800 k€. This example shows that even with the currently very volatile prices, the arbitrage earnings are not of a magnitude that can pay back a battery within 10 years. It would take 18 years for a 50 kV connected customer in 2022 with very low tariffs and 20 years for a B-low 400 V connected customer with higher tariffs. The tariff level makes a significant difference for the business case.

Table 6 *Payback time of a battery with a cost of 800 k€ performing only arbitrage*

	A-high	A-low	B-high	B-low	C
2017	613 years	676 years	809 years	930 years	1757 years
2018	336 years	359 years	407 years	451 years	721 years
2019	507 years	566 years	668 years	762 years	1551 years
2020	200 years	216 years	245 years	273 years	479 years
2021	56 years	59 years	63 years	66 years	82 years
2022	18 years	18 years	19 years	20 years	23 years

The limited earnings are caused by the fact that large price differences are occurring with a low frequency, which limits the number of energy exchanges. If the battery is installed behind the meter with consumption and a well dimensioned PV system, the earnings from arbitrage can, to some extent, be combined with the savings from behind the meter optimisation.

3.5 Ancillary Services

To maintain the stability of the electricity grid, electricity consumption and production must be in constant balance down to the second time scale. The balance can be observed on the short time scale by the system-frequency in the electricity grid, which is normally 50 Hz with minor fluctuations. If the frequency starts deviating, it indicates a mismatch between consumption and production.

To maintain the balance, Energinet purchases services from production and consumption resources, which can be activated to restore the balance. Since the balance is monitored by measuring the frequency, this is called frequency regulation. Frequency Containment Reserve (FCR) is often referred to as primary reserve, because it is the first to respond to grid disturbances. The name refers to the function of the reserve, which is to contain a sudden drop in grid frequency. **Figure *12*** shows an example of how the grid frequency drops due to a sudden loss of generation capacity.

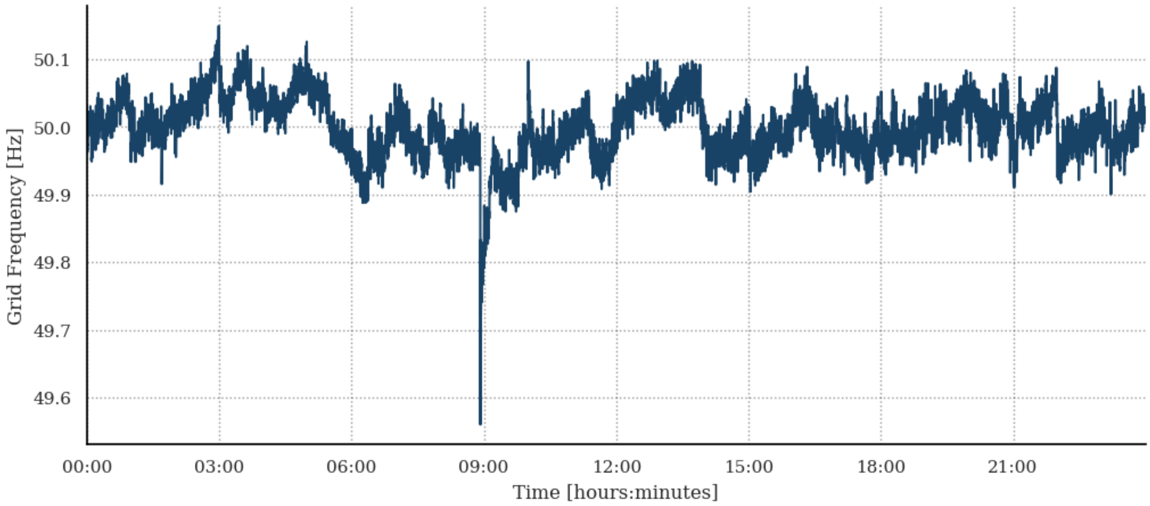


Figure 12 *Measured frequency in the Nordic Grid: 02/07/2021.*

Frequency fluctuations differ from a grid system to another, depending on the size of the system penetration of renewables, the presence of rotating conventional power plants and the extend of provision of frequency containment reserves.

Historically, the frequency deviations are less pronounced in the Continental European grid when compared to the Nordic Grid. **Figure *13*** and **Figure *14*** show the frequency distributions in the Nordic and Continental grids, respectively, from measurements performed in 2022 by Hybrid Greentech, by frequency meters installed during Alight project.

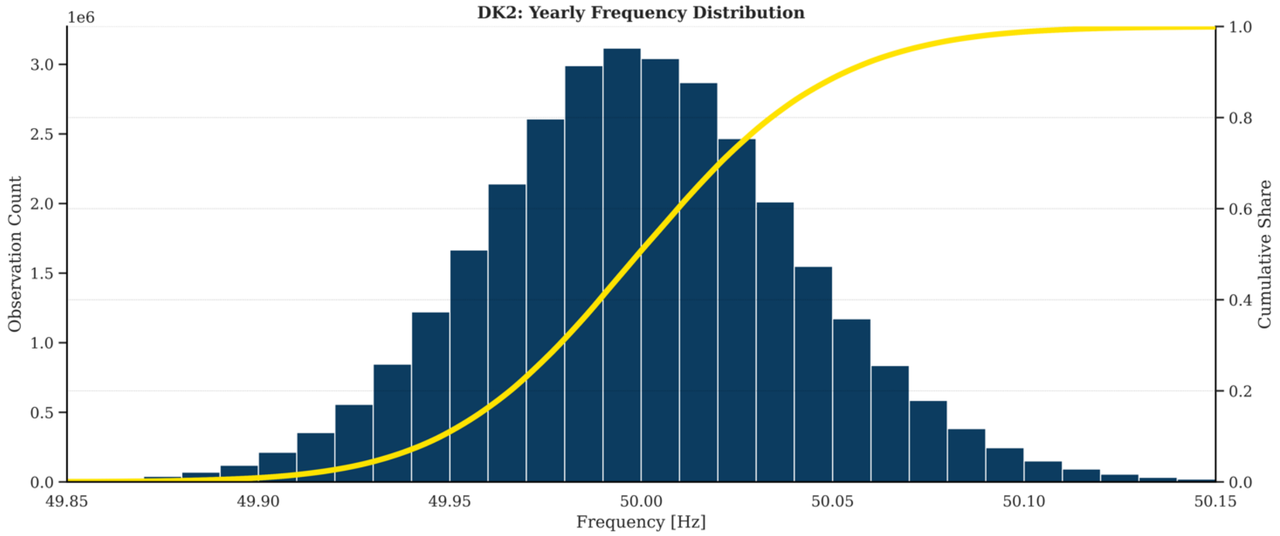


Figure 13 *Distribution of Nordic grid frequency for the year 2022*

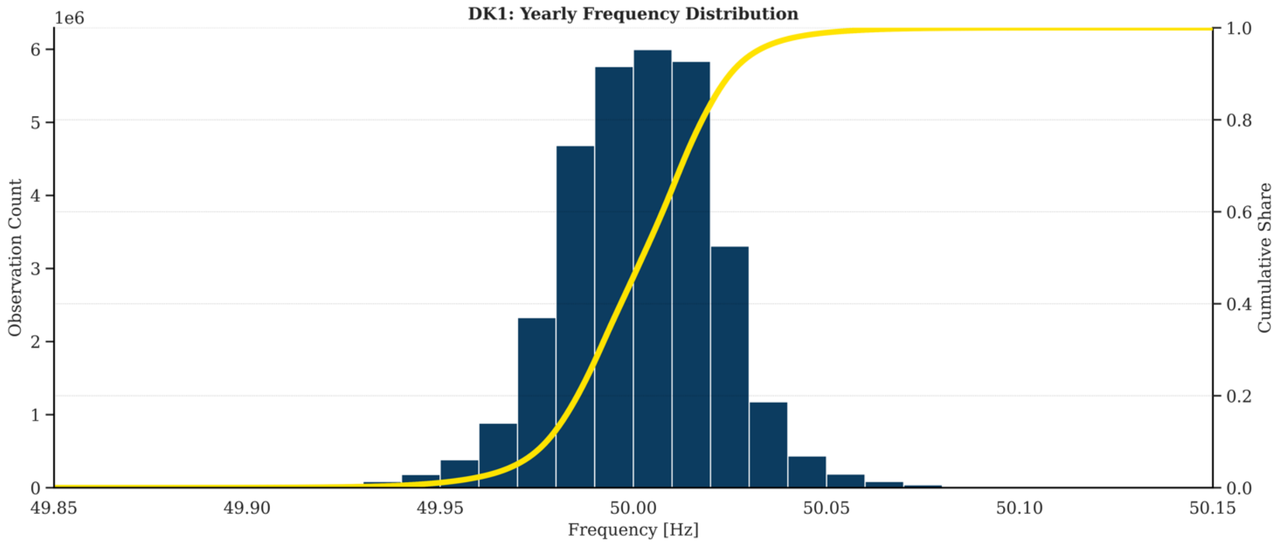


Figure 14 *Distribution of Continental European grid frequency for the year 2022*

The measurements show that the frequency deviations are significantly higher in the Nordic grid compared to the Continental grid, which is related to the much smaller size, and thereby inertia, of the Nordic grid compared to the Continental grid.

The frequency services consist of either up- or downregulation or both (a symmetric service). Upregulation refers to the act of increasing the frequency, while downregulation refers to the act of reducing the frequency. An overview of the services is given in **Table 7**.

Table 7 *Overview of consumers and producers' response to deviation in system frequency*

System state	**Under-frequency**	**Over-frequency**
Activity	Upregulation	Downregulation
System state	Demand exceeds supply	Supply exceeds demand
Producer	Increase power supply to balance the grid.	Decreases the power being supplied to balance the grid.
Consumer	Decreases consumption to balance the grid.	Increases consumption to balance the grid.

A regular charger, a V2G charger or a battery can supply both production (when discharging or stopping charging) and consumption (when increasing charging) to the power grid.

Services present in Denmark include FCR, FCR-D, FFR, FCR-N, aFRR, and mFRR. Different services are procured by the TSO depending on the location of the asset in the grid.

<u>**In DK1**, the services that can be provided are FCR, aFRR and mFRR:</u>

FCR (Frequency Containment Reserves) is power capacity (MW) for a *symmetric* service that requires a moderate amount of activation, as it is activated when the frequency deviates from 50 Hz, with only a small deadband between 49.98 Hz and 50.2 Hz, where no activation is required. The power should be implemented linearly for frequency deviations of up to 200 mHz, giving full power charging at 50.2 Hz and full power discharging at 49.8 Hz. The *first* response should happen within 2 s, 50% within 15 s and full power should be delivered in 30 s and be able to hold it for 15 minutes. It is paid for availability (€/MW) in 1 MW increments and minimum 1 MW bids using *marginal pricing* at daily auctions for 4-hour blocks. Limited energy storage units can only bid 80% of the rated power.

aFRR (Automatic Frequency Restoration Reserve) is the secondary control of the power system, where Energinet directly controls the power setpoint (MW) to the BRP, which then distributes it to the *larger and slower power plants* to bring the frequency back to 50 Hz and relieve the primary FCR service. Full power should be delivered in 15 minutes. It is traded as a *symmetric* service using *pay-as-bid* for availability (€/MW) in 0.1 MW increments and minimum 1 MW bids at a weekly auction for availability all hours of the week. The service *requires large bulk energy exchanges*. Production is settled with the highest of the spot price plus 100 DKK/MWh, and the upregulating power price and consumption is settled with the lowest of the spot price minus 100 DKK/MWh and the downregulating power price.

mFRR (Manual Frequency Restoration Reserve) is for *even larger and slower units* that should relieve the aFRR service after the frequency is back to 50 Hz. Energinet pays market actors availability payment (€/MW) for upregulation capacity (MW) to guarantee to bid potential additional energy generation (MWh) in the real time regulating power market (€/MWh).

Anyone can bid in the regulating power market (voluntary bids), but the mFRR participants are obligated to. Energinet activates the energy bids it needs to cover *large energy imbalances*. Units that are expensive to activate can offer a low price to the availability mFRR auction and a high price to the regulating power market. It is, however, required that the unit can be activated *continuously for 8 hours* to be allowed continuous availability payment. Availability of mFRR is paid using *marginal pricing* and traded in 0.1 MW increments and minimum 5 MW bids at daily auctions for individual hours. Energy activations of production is settled with the upregulating power price, while consumption is settled with the downregulating power price.

In DK2, the services that can be provided are FCR-D up, FCR-D down, FCR-N, FFR, aFRR and mFRR:

FCR-N (Frequency Containment Reserves for Normal Operations) is a *symmetric* service that requires a *considerable amount of activation*, as it is activated whenever the frequency deviates from 50 Hz, which it *always* does to some extent. The service can be delivered by *medium speed units*, as the first response. 63% of which must be supplied within 60seconds and 95% within 3 minutes. The power should be implemented linearly for frequency deviations of up to 100 mHz, giving full power charging at 50.1 Hz and full power discharging at 49.9 Hz. It is paid for availability (€/MW) in 0.1 MW increments and minimum bid size of 0.1 MW using *pay-as-bid* on a daily auction for each hour. A capacity of *98 MW can be delivered from DK2* (the full Danish fraction and 1/3 of the Swedish fraction).

FCR-D Up (Frequency Containment Reserves for Disturbances) is an *upregulation* service to balance the grid frequency for *larger disturbances*. The first response should happen owithin 2.5 seconds, and 86% within 7.5 seconds. FCR-D Up is activated whenever the grid frequency drops below 49.9 Hz, and the power should be linearly implemented for frequency deviations up to 500 mHz (49.5 Hz). It is paid for availability (€/MW) in 0.1 MW increments and minimum bid size of 0.1 MW using *pay-as-bid* on a daily auction for each hour. A capacity of *237 MW can be delivered from DK2* (the full Danish part and 1/3 of the Swedish part). There is *no settlement of activated energy*.

FCR-D Down (Frequency Containment Reserves for Disturbances) is a *downregulation* service to balance the grid frequency for larger disturbances: Like FCR-D Up, *the activation is very limited*. The first response should happen within 2.5 seconds, and 86% within 7.5 seconds. FCR-D Down is activated whenever the grid frequency exceeds 50.1 Hz, and the power should be linearly implemented for frequency deviations up to 500 mHz (50.5 Hz). It is paid for availability (€/MW) in 0.1 MW increments and minimum bid size of 0.1 MW using *pay-as-bid* on a daily auction for each hour. A battery or a bi-directional V2G charger can *deliver FCR-D Up and Down at the same time* and get paid for both. A capacity of *237 MW can be delivered from DK2* (The full Danish part and 1/3 of the Swedish part).

FFR (Fast Frequency Regulation) is a very fast *upregulation* reserve that is *only purchased for hours with low inertia in the grid* to mitigate larger disturbances. It is a step response service that requires full power delivered when the frequency goes below a threshold. The activation happens at 49.5, 49.6 or 49.7 Hz depending on if the plant can deliver the full response in 0.7, 1.0 or 1.3 s, such that faster units are activated less often. It is paid for availability (€/MW) in 0.1 MW increments and minimum bid size of 0.3 MW using *marginal price* on a daily auction with for each hour. A capacity of *45 MW can be delivered from DK2*.

aFRR (Automatic Frequency Restoration Reserve) in DK2 is like the service in DK1, except *up- and downregulation is traded separately* for each hour with availability paid using *marginal pricing* (€/MW) on a daily Nordic auction. Full power should be delivered in 5 minutes and be withheld for as long as the service is provided (up to 8 hours). Production is settled with the upregulating power price and consumption is settled with the downregulating power price.

mFRR (Manual Frequency Restoration Reserve) in DK2 is the same as in DK1.

aFRR and mFRR are for bulk energy deliveries and are suitable for power generation or consumption that can be interrupted for up to 8 hours. It is not a good match with energy storage with limited capacity and electric vehicle charging. Therefore, the analysis focuses on the primary reserves, which are mainly based on availability of power and not significant energy delivery.

Table *8* shows a summary of the technical requirements of the primary frequency regulation reserves in DK1 and DK2. FCR-N and FCR-D Up and Down are traded twice, as Energinet purchases 80% of the capacity on the early auction on 00:30 and 18.00 on the day before operation.

		FCR	FCR-N	FCR-D	FFR
Bidding Requirements	Minimum Bid	0.1 MW	0.1 MW	0.1 MW	0.3 MW
	BRP Conditions	BRP Required	BRP Required	BRP Not Required	BRP Not Required
	Total Volume	+-23 MW	DK, 18 MW SE, 240 MW	DK, 44 MW SE, 580 MW	DK, 0 - 45 MW
	Bid Submission	D-1, no later than 8:00	D-1 early, no later than 00:30 D-1 late, no later than 18:00	D-1 early, no later than 00:30 D-1 late, no later than 18:00	D-1, Bids must reach Energinet by 15:00
	Bid Information	Hourly volume and price	Hourly volume and price	Hourly volume and price	Hourly volume and price
Participation Requirements	Activation Frequency	+200mHz -200mHz	+100mHz -100mHz	Below 49.9 Hz Above 50.1 Hz	+300mHz
	Tolerance Area	+15% -5%	+15% -5%	+15% -5%	+15% -5%
	Response Time	Within 2 sec >50% within 15 sec 100% within 30 sec	63% within 60 sec 95% within 3 min	2.5 sec 86% within 7.5 sec	49.7, 49.6, 49.5 Hz in 1.3, 1.0, and 0.7 sec
	SCADA Reporting	Better than 1 sec Signal stored for 1 week	Better than 1 sec Signal stored for 1 week	Better than 1 sec Signal stored for 1 week	Better than 1 sec Signal stored for 1 week
	Required Accuracy	Better than +- 10 mHz	Better than +- 10 mHz	Better than +- 10 mHz	Better than +- 10 mHz
	Response duration	Min 4 hours LERs, min 24 min	Continuously LERs, min 1 hour	SC, SNC, within 15 min LERs, min capacity 20 min	Min 15 min
Performance Requirements	Performance Types			Dynamic • Continuous (DC) • Non-Continuous(DNC) Static • Continuous (SC) • Non-continuous (SNC)	Long Support Short Support
	Compliance Tests		Step response test Sine reponse test	Fast ramp test (DC, DNC) Sine reponse test (DC, DNC)	Synhetic frequency signal, to verify time, volume, activation
			Linearity test	Ramp static test (SC, SNC) Linearity test (SC, SNC, DNC)	Natural frequency signal, to verify time, volume
	Limited Energy Management	Normal state (NEM) Alert state (AEM)	Normal state (NEM) Alert state (AEM)	Normal state (NEM) Alert state (AEM)	

Table 8 *Overview of the technical requirements for fast reserves*

3.5.1 **Limited Energy Reservoirs (LER) Requirements**

The Nordic TSOs have defined a new set of power and energy delivery requirements for systems falling under the Limited Energy Reservoirs (LER) category. The new FCR requirements came into effect on September 1, 2023. These are as follows:

BESS can operate in three modes:

- Normal operation
- Normal energy management (NEM)
- Alert energy management (AEM)

BESS operates in NEM mode to restore energy. BESS operates in AEM mode to be considered unable to deliver services. BESS is required to set aside specific MWs of power for NEM. It cannot bid in the market on these MWs power. BESS enters NEM or AEM, when the frequency deviations are within a specific range and the BESS has an ability to provide specific minutes of energy at full response in both directions. The range for frequency deviations and minutes of energy differ for each service and follow following equations:

$$\mathrm{NEM}_{\mathrm{Allowed}} = \begin{cases} -1 & if \quad f_{min} < f < f_{max} \ \ and \ \ SOC < SOC_{up} \\ +1 & if \quad f_{min} < f < f_{max} \ \ and \ \ SOC < SOC_{down} \\ \quad 0 & \qquad otherwise \end{cases}$$

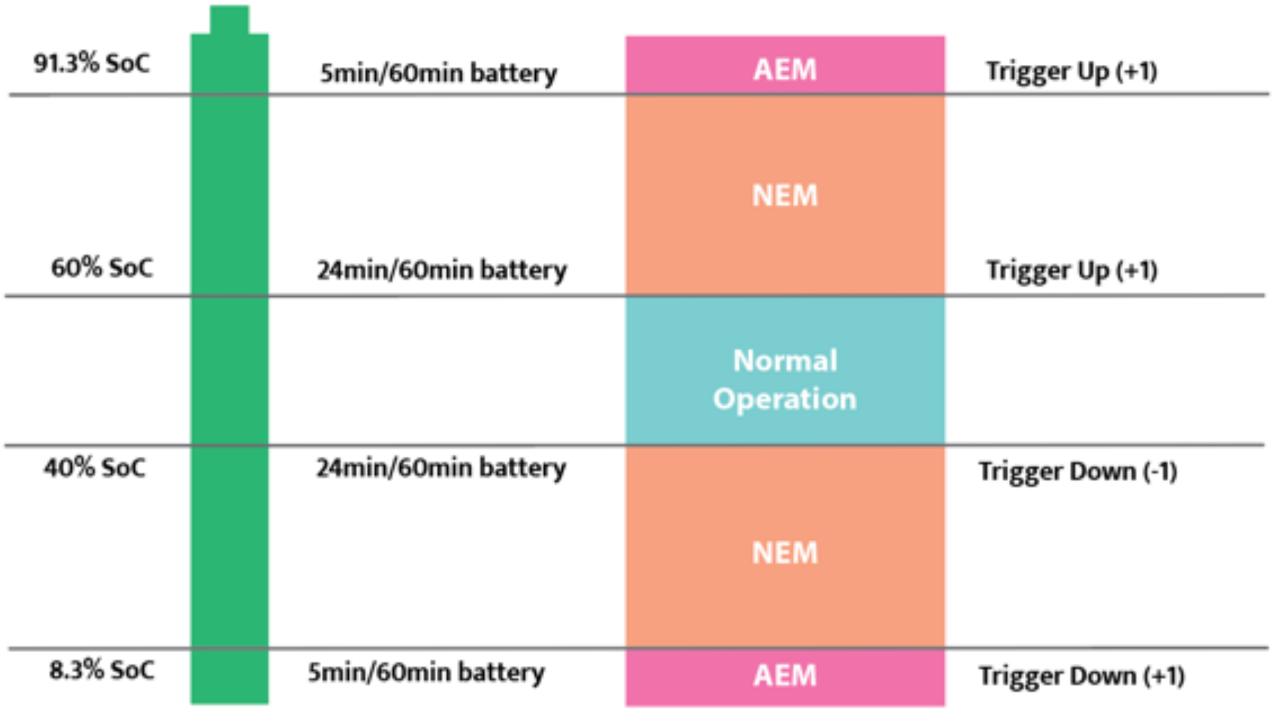
$$\mathrm{NEM}_{\mathrm{current(ti)}} = \frac{1}{N} \sum_{n=1}^{N=300} NEM_{allowed(ti-n)}$$

$$\mathrm{P}_{\mathrm{total,service}} = \mathrm{P}_{\mathrm{service}} + \mathrm{factor} \; . \; \mathrm{C}_{\mathrm{service}} \; . \; \mathrm{NEM}_{\mathrm{current}}$$

Here factor take different values for each service:

For FCR, factor = 0.25, FCR-D, factor = 0.2, and for FCR-N, factor = 0.34

BESS providing FCR must reserve 25% power for NEM. For a BESS of 1.25 MW/1 MWh, this would mean 0.25*(1.25 + 1.25) MW reserved for NEM. NEM mode is triggered (+1,-1), when the frequency deviations are within +-50mHZ AND the BESS is at energy level >24 minutes of FCR capacity in each direction. Changing NEM setpoint is implemented 20% per minute. The transition must occur within 5 minutes. AEM mode is triggered when the BESS is at energy level < 5 minutes of FCR capacity in each direction. AEM can use the full rated power. When AEM is activated the frequency reference is altered from the usual 50 Hz. It is changed to the avergae frequency of past five minutes. The figure below illustrates NEM and AEM activation for 1.25 MW/1 MWh BESS



For a 1-hour system, the following constraints apply.

- **For FCR-N**, the system is required to reserve an energy capacity equivalent to delivering the full bid capacity for 2.5 hours (1.25 hours discharge and 1.25 hours of charge). A maximum of 66% of the rated power can be sold for FCR-N.
- **For FCR-D Up**, the system is required to reserve an energy capacity equivalent to delivering the full bid capacity for 20 minutes (0.33 hours). 20% of the bid capacity should be reserved in the opposite direction to allow for recharging after the service has been provided.
- **For FCR-D Down**, the system is required to reserve an energy capacity equivalent to delivering the full bid capacity for 20 minutes (0.33 hours). 20% of the bid capacity should be reserved in the opposite direction to allow for recharging after the service has been provided.
- **For FFR**, there are no requirements for reserving power or energy.

The description above is formulated as four equations that the objective function of the optimization is subject to:

$$P_{capacity}^{discharge} \geq P_{FCRN} * 1.34 + P_{FCRD\ up} + P_{FCRD\ down} * 0.2 + P_{FFR}$$

$$P_{capacity}^{charge} \geq P_{FCRN} * 1.34 + P_{FCRD\ down} + P_{FCRD\ up} * 0.2$$

$$E_{energy}^{stored} \geq P_{FCRN} * 1.25\ h + P_{FCRD\ up} * 0.33\ h$$

$$\left(E_{energy}^{max} - E_{energy}^{stored}\right) \geq P_{FCRN} * 1.25\ h + P_{FCRD\ down} * 0.33\ h$$

For a 1 MW / 1 MWh BESS, the delivery of ancillary services is required to abide by the limits for different market combinations shown in **Table *9***.

Table 9 *Requirements for 1 MW / 1 MWh BESS*

Market Combinations	Max Bid Capacity	Blocked Power	Duration Requirement	Minimum State of Energy (Out of 10 MWh)	Maximum State of Energy (Out of 10 MWh)
FCR-N	0.4 MW	0.6 MW (133%)	2.5 hours	0.5 MWh	0.5 MWh
FCR-D Up	1 MW	1 MW	20 min	0.33 MWh	1 MWh
FCR-D Down	1 MW	1 MW	20 min	0 MWh	0.67 MWh
FFR	1 MW	1 MW	30 s	1 MWh	1 MWh
FCR-D Up + Down	0.8 MW/0.8 MW	1/1 MW	20/20 min	0.264 MWh	0.736 MWh
FFR + FCR-D Down	0.8 MW/1 MW	1/1 MW	30 s/20 min	1 MWh	0.67 MWh

A 2-hour BESS does not need to reserve power in the opposite direction for recharging when delivering FCR-D Up and Down. For a 1 MW / 2 MWh BESS, the delivery of ancillary services is required to abide by the requirements shown in the following equations:

$$P_{capacity}^{discharge} \geq P_{FCRN} * 1.34 + P_{FCRD\ up} + P_{FFR}$$

$$P_{capacity}^{charge} \geq P_{FCRN} * 1.34 + P_{FCRD\ down}$$

$$E_{energy}^{stored} \geq P_{FCRN} * 1.25\ h + P_{FCRD\ up} * 0.33\ h$$

$$\left(E_{energy}^{max} - E_{energy}^{stored}\right) \geq P_{FCRN} * 1.25\ h + P_{FCRD\ down} * 0.33\ h$$

The limits for the relevant market combinations are shown in **Table *10***.

Table 10 *Requirements for 1 MW / 2 MWh BESS*

Market combinations	Max bid Capacity	Blocked Power	Duration Requirement	Minimum State of Energy (Out of 2 MWh)	Maximum State of Energy (Out of 2 MWh)
FCR-N	0.66 MW	1 MW	2.5 hours	0.5 MWh	0.5 MWh
FCR-D Up	1 MW	1 MW	20 min	0.33 MWh	2 MWh
FCR-D Down	1 MW	1 MW	20 min	0 MWh	1.67 MWh
FFR	1 MW	1 MW	30 s	0.1 MWh	2 MWh
FCR-D Up/Down	1 MW/1 MW	1/1 MW	20 /20 min	0.33 MWh	1.67 MWh
FFR/FCR-D Down	1 MW/1 MW	1/1 MW	30 s/20 min	0.1 MWh	1.67 MWh

In general, the new regulations for LER favorize larger storage systems. However, a 2-hour energy system adds a significant investment cost compared to a 1-hour storage system, while contributing at most by 25% (FCR-D) and 65% (FCR-N) in bid capacities. Since FCR-N is the most demanding service regarding activation, it is already a very limited number of hours per year where it makes sense to provide FCR-N with the current regulation.

3.5.2 Power Activation and Energy Throughput

The amount of activation has a large impact on the cost of delivering the services. The activation is a function of the service frequency behaviour, which varies significantly for different synchronous zones. This section presents the required activation for different services based on real frequency measurements for one year.

FCR-N and FCR

Figure *15* shows the distribution in magnitudes of FCR-N activations during a year. FCR-N is constantly activated with equal amounts of upregulation and downregulation. The x-axis shows the magnitude of the activations in terms of power, while the y-axis shows the accumulated duration over the year for the power interval.

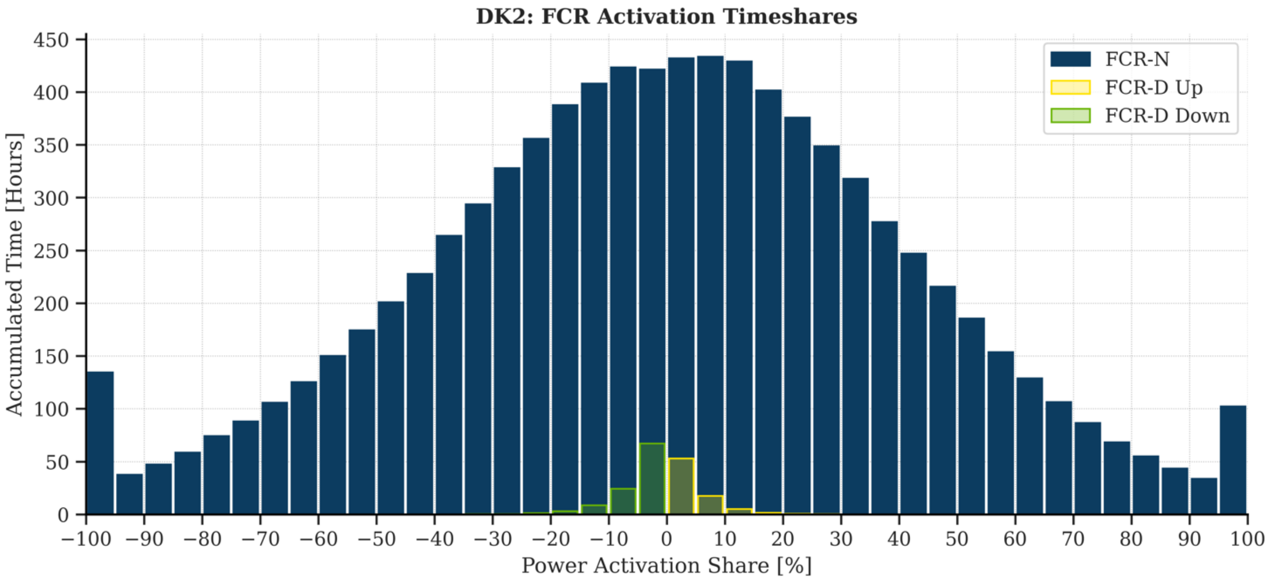


Figure 15 *Accumulated hours per share of activated power for FCR-N, FCR-D Up and FCR-D Down*

Figure *16* shows the same calculation for FCR in DK1. FCR is activated at twice as large deviations as FCR-N, while at the same time being in a grid with only half the deviations, it has much fewer activations than FCR-N – and with power activations of smaller magnitude.

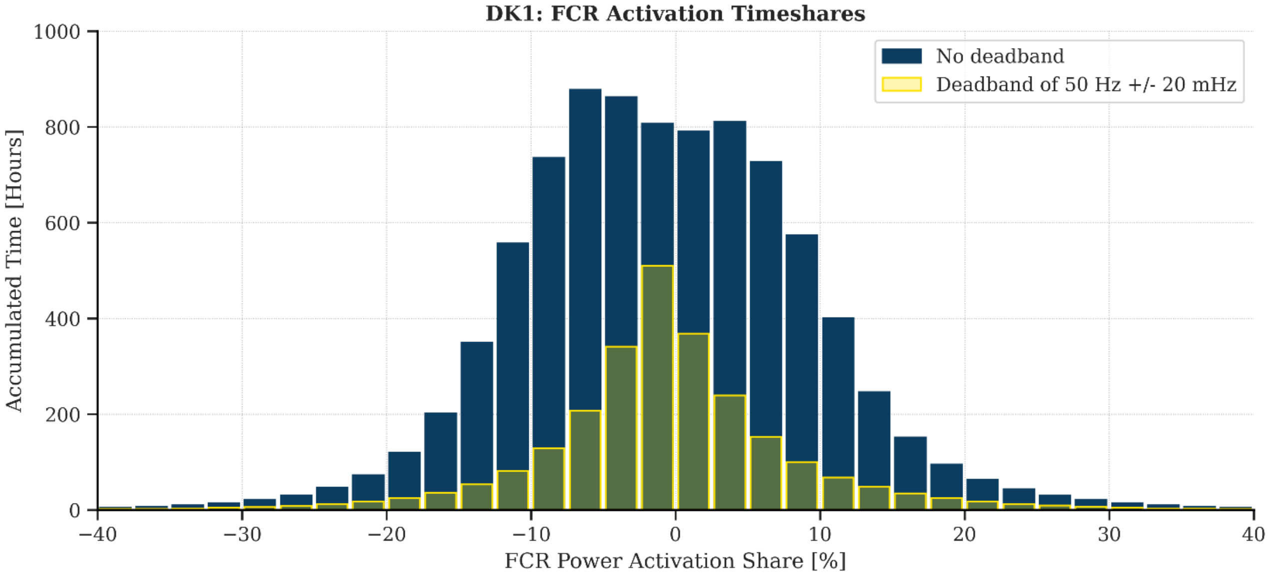


Figure 16 *Accumulated hours per share of activated power for FCR*

Constantly delivering 1 MW FCR-N service throughout a year required a cumulated 2.8 GWh of energy throughput, split equally between upregulation and downregulation. That corresponds to 1.400 charge/discharge cycles for a 1 MW / 1 MWh battery.

One year of FCR delivery with 1 MW only required an energy throughput of 0.76 GWh, corresponding to only 380 charge/discharge cycles.

There is an activation of the FCR market almost every hour, requiring a certain amount energy delivery/consumption as seen in **Figure *17***. However, as seen in **Figure *16***, the magnitude of most responses is small, as almost every response is between -25% and 25% power activation. As also showcased by **Figure *17***, it is desirable to provide FCR with deadband, because the daily energy throughput is much lower than the case of no deadband.

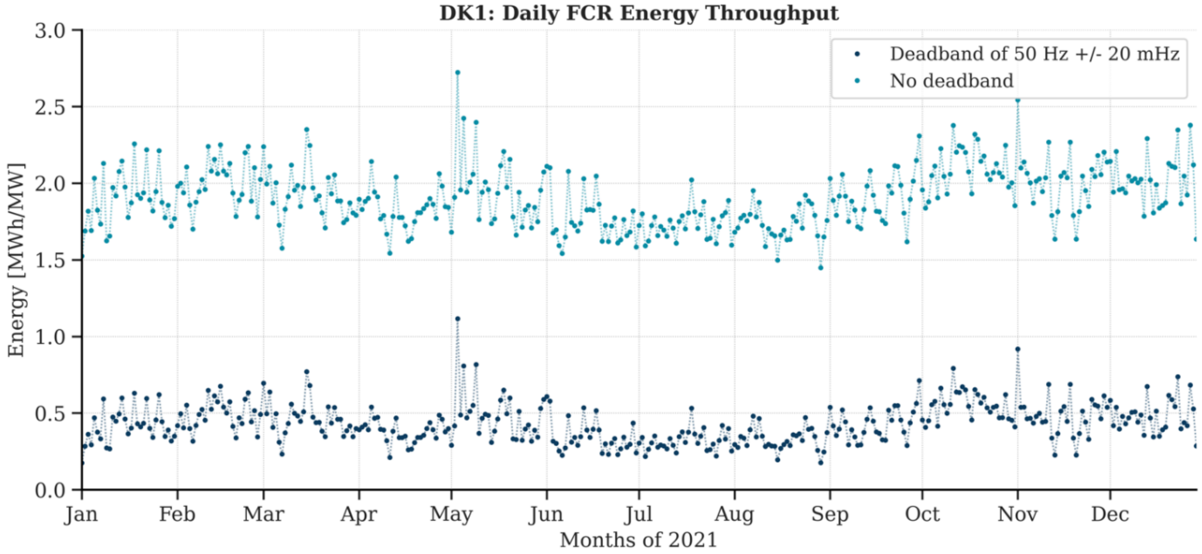


Figure 17 *Daily energy throughput in the FCR market*

FCR-D Up & Down

FCR-D has very little activated power, as shown in **Figure *18***. The purpose of this service is to provide fast reserves in case of significant disturbances like faults on interconnectors or major power plants. The combined throughput for both FCR-D Up and FCR-D Down is less than 10 MWh per year for a 1 MW asset. There is no activation 99% of the time.

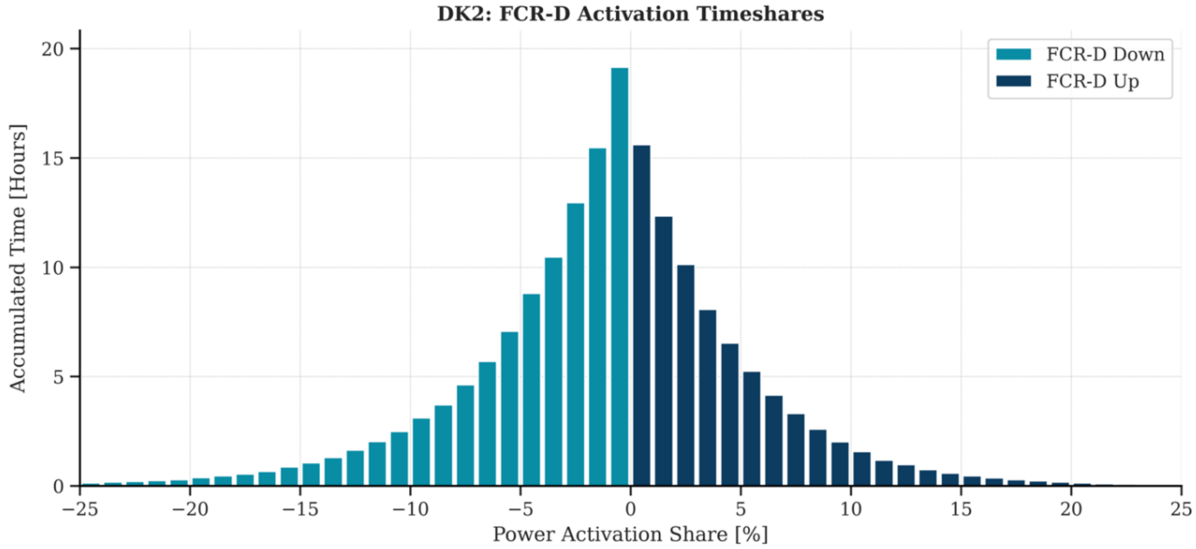


Figure 18 *Accumulated hours per share of activated power for FCR-D*

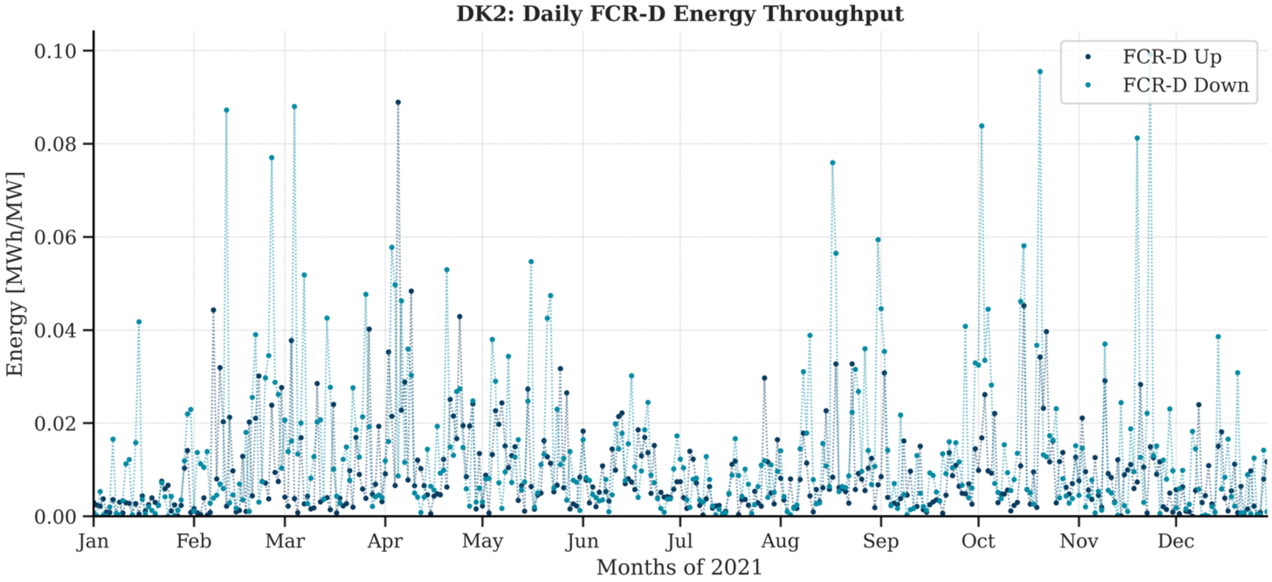


Figure 19 *Daily energy delivery for FCR-D Up and for FCR-D Down throughout 2022*

Further highlighting the low activation share of FCR-D, Figure 19 shows the extremely low daily energy throughput compared to that of FCR in **Figure *17***. Most of the time, the daily energy throughput is below 0.02 MWh/MW. As such, FCR-D is very attractive for BESS assets and EVs.

FFR

From May 2020 to September 2022, has there only been two incidents requiring activation of power for 30 s each, so there has been virtually no cost of activation (Energinet, 2022). Larger deviations can also occur more regularly, as there has been large faults on both on January 12, 2023 (49.60 Hz) and February 17, 2023 (49.45 Hz). These were measured with the frequency meters developed in the Alight project. Energinet was not procuring FFR in those hours, so they did not trigger an FFR activation. The low chances for this kind of large frequency drop, coupled with the TSO's intermittent purchasing of the FFR reserves, reduces the odds of FFR activation. It is, however, purchased in quite small amounts.

3.5.3 Energy Throughput of Each Market

Frequency Containment Reserves

The mentioned ancillary services will require the battery to import and export energy during operation. The throughput for delivering each of the services is summarized in the table below. **Figure *20*** showcases the daily energy throughputs of the primary reserves.

Table 11 *Yearly energy throughput in MWh per MW capacity per service for the year 2022*

FCR-N	2,711 MWh (1,355 charge cycles)
FCR-D Up	3.2 MWh (1.6 charge cycles)
FCR-D Down	4.3 MWh (2.1 charge cycles)
FFR	0.075 MWh (0 charge cycles)

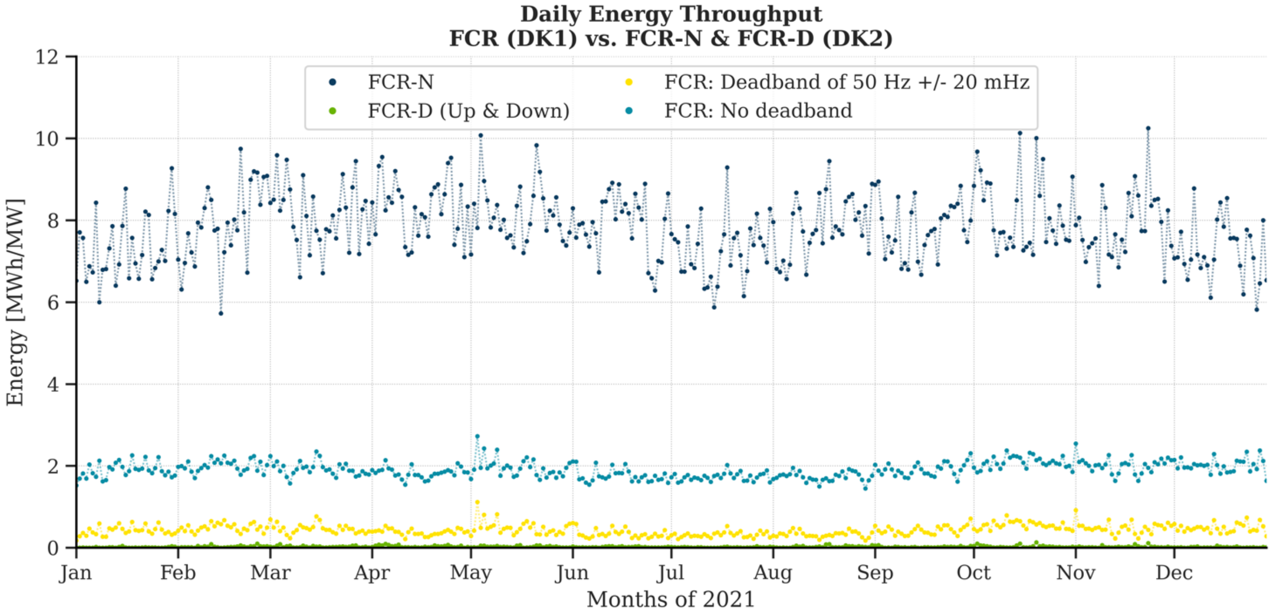


Figure 20 *Daily energy throughput for FCR-D, FCR-N and FCR*

As seen, FCR-N has by far the largest energy throughput, with the most attractive services being FCR-D and FCR (no deadband) for BESS assets and EVs.

Frequency Restoration Reserves

BRPs can also trade energy real-time directly with Energinet, with reference to their schedules, to cover system imbalances. This is called the regulating power, which Energinet uses to cover large imbalances.

BRPs sell energy at the upregulating power price in €/MWh, which is determined by the demand at that instance and the offers of regulating power providers to increase their power output. The price is higher than or equal to the spot price. Similarly, BRPs can buy back energy at the downregulating power price, which is lower than or equal to the spot price. In this case, the BRP delivering downregulating power will pay Energinet a lower price for not producing a certain amount of energy that was already sold in the day ahead market at a higher price, resulting in the BRP earning the price difference.

Figure *21* shows the spot prices alongside up- and downregulation power prices in DK2 during a week of 2022. The regulating power prices offers higher price volatility, but the price is not known in advance. It is possible to make a bid/offer in €/MWh in one of the directions and then wait until the time of operation to see if Energinet will activate it. The bid/offer can be made with a price close to the spot price if frequent activation is intended. Energinet activates the cheapest assets first, but all assets receive the same payment as the most expensive activated asset. There can be several days between activation, depending on the imbalances in the system.

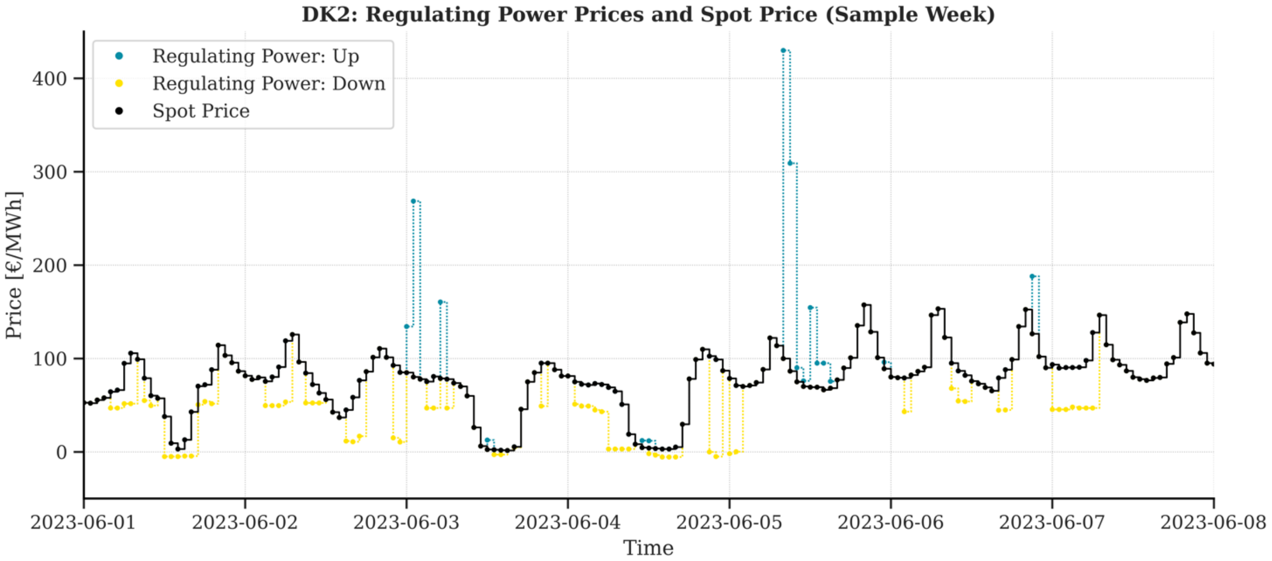


Figure 21 *Sample of spot price and regulation power prices in DK2*

If a group of EVs are charging with 10 MWh in an hour at a spot price of 300 €/MWh and are activated to upregulate (stop charging) with a price of 600 €/MWh, the idle EVs can be sold as downregulation capacity (start charging) in the following hours at 200 €/MWh, which results in earnings of (600 – 300 – 200 €/MWh) • 10 MWh = 1000 €.

3.5.4 **Local Flexibility at Distribution Level**

Local flexibility at the distribution level is the sale of services to the DSO to resolve congestion in the local distribution grid. The goal is to reduce investments by choosing flexibility services over infrastructure expansions, thereby reducing the total cost of distribution. It is not yet possible to sell local flexibility to the DSO in Denmark, as no functioning framework for the services have been developed.

According to European regulations, DSOs are required to develop their grid according to a transparent network development plan (NDP), which must be published every second year. These regulations were introduced as part of the implementation of the Clean Energy Package for All Europeans in 2019, which aims to strengthen a flexible electricity market throughout Europe. This package also introduced a new market participant, known as an aggregator. The aggregator can sell the adjustable charging schedule to the DSO from a portfolio of smaller units. This may require new ways of digital communication, such as market interfaces and improved access to infrastructure data. To address the challenges that will arise during the implementation of local flexibility at the distribution level, a new European organization called E.DSO has been formed.

The DSO at CPH is Radius Elnet A/S. Radius' grid development plan shows that they expect a total flexibility need of 60 MW and an investment need of 134 M€ during the next 0-2 years [5]. Radius do, however, not foresee any need for flexibility near the CPH airport. Therefore, in the specific case, it is unlikely that CPH can provide local flexibility services during the next 6-10 years. The grid development plan was first drafted as of April 2022 and was later approved by the Danish Utility Regulator in December 2022.

It is not yet possible to sell flexibility services at market terms in Denmark, but the DSOs expect it to be introduced within 5-10 years.

3.5.5 Local Flexibility at the Transmission Level

Local flexibility at the transmission level is handled by providing services to the transmission system operator (TSO) to resolve congestion in the transmission network within a price zone and to avoid downregulation and curtailment of renewable energy production. The goal is to reduce investments by choosing flexibility services over infrastructure expansions, thereby reducing the total cost of transmission. This service is in many ways like local flexibility at the distribution level, except that the implementation is in the transmission phase.

In Denmark, local flexibility at transmission level will as of medio 2023 is managed via the Manual Frequency Restoration Reserves Energy Activation Market (mFRR EAM). The Danish TSO will, from the end of 2023, require a so-called Geotag on all bids/offers, which enables the TSO to map where flexibility is located. Local congestion can then be dealt with by activating the cheapest local flexibility and reject flexibility that worsen the situation. The minimum bid/offer size is 1 MW, which means that a large portfolio of smaller assets would need to be aggregated. Production from renewable sources on land is planned to be quadrupled towards 2030 so the TSOs congestion management is expected to increase in frequency.

3.5.6 Economic Value of Delivering Frequency Regulation

Most of the Nordic ancillary service markets have had increasing prices during the previous four years. The ancillary services are mainly being delivered by Nordic hydro power plants, which are very spot price sensitive. This implies that it is costly for the plant to be operating in hours of low spot prices and costly not to operate at full capacity in times of high spot prices.

Figure *22* shows aggregated earnings per MW over periods of two months from providing select ancillary services constantly 24 hours per day throughout each month. The availability payment is generally highest during the summer, due to the lower water level in the Nordic reservoirs. The low prices of 2020 were caused by an unusually high amount of precipitation. A contributing factor to lower prices during winter is the presence of combined heat and power (CHP) plants operating with the primary purpose of delivering heat and co-delivering FCR services at the same time, despite the electricity generation itself not being profitable.

FCR-D Up has historically had lower prices than FCR-N, as there is almost no activation, resulting in less wear and tear.

The much stricter response time requirements, however, mean that it is a subset of assets able to deliver FCR-D, compared to FCR-N. As an example, the first Danish commercial deployment of V2G chargers at Frederiksberg Forsyning are delivering FCR-N even despite the constant activation causing a significant cost for conversion losses and battery degradation, compared to delivering FCR-D. The 6-second response time of the chargers is not fast enough to live up the FCR-D requirements (Zecchino, Thingvad, Andersen, & Marinelli, 2019).

The payment for FCR-D has increased and has been on the same level as FCR-N in the last two years. Assets that can regulate in both directions, like V2G, can deliver and be paid for FCR-D Up and FCR-D Down at the same time. When delivering both services at the same time, the payment of FCR-D far exceeds the capacity payment of FCR-N. FCR-D also has a seasonality pattern, but the trend is less clear than for FCR-N.

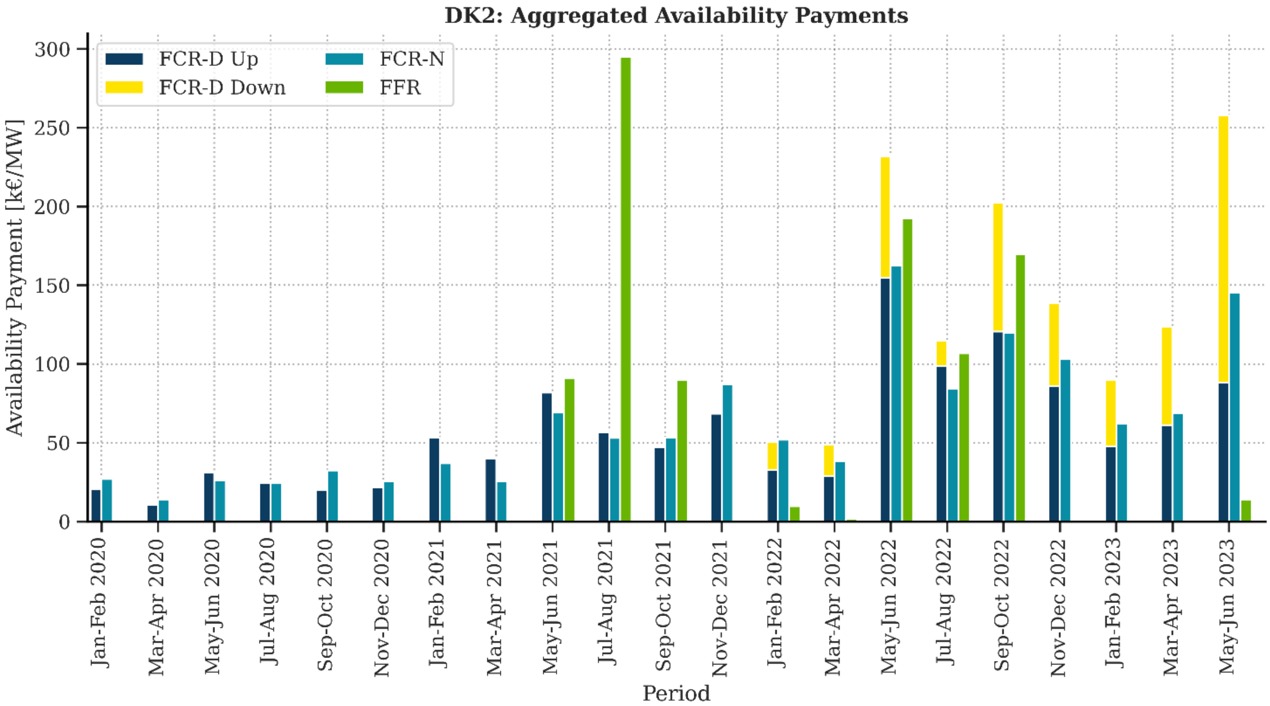


Figure 22 *Aggregated availability payment of FCR-D Up and FCR-D Down over periods of two months*

FFR generally has significantly higher prices than FCR-D and FCR-N in the hours where it is purchased. FFR is, however, only purchased 19% of the time with an average purchase of 7 MW and a maximum purchase of 28 MW. FFR is a small market with a high risk of market saturation, but Energinet expects their demand to increase 400-800% during the next decade (Energinet, 2022).

Figure *23* shows the FCR prices in DK1 and in Germany. DK1 has experienced very high prices after the reserve was made symmetric in January 2021, as very few actors were able to deliver both upwards and downwards capacity. During the first seven days of September, a battery in Germany earned 3.9 k€/MW, while a battery in Western Denmark earned 61.2 k€/MW (16 times more). A battery that could bid 1 MW in DK1 would have earned 1.1 M€ during 2022, which is more than enough to pay back the entire investment.

The Danish core share of DK1 was removed on September 7, 2022, such that the whole Danish FCR reserve could be delivered from Continental Europe. The earnings in Western Denmark are now equal to those in Germany, Austria, Belgium, France, Netherlands, Slovenia and Switzerland (who all have the same prices).

The huge size of the continental European FCR market of 3000 MW also means that there is a very low risk of the European prices suddenly dropping due to market saturation. This risk is also reduced for Danish actors after the FCR export limit was increased from 20 MW to 100 MW on the 1st of October 2022. Danish actors can now deliver 100 MW FCR into Germany.

The business case for FCR in DK1 is not as profitable as in DK2, where the market is still showing increasing prices. DK2 is already completely merged with Sweden, which reduces the risk of sudden market saturation, as the markets are quite large.

Despite DK1 now having European prices, the last two years of FCR prices still makes it the most profitable use case for a battery and results in a reasonable payback time of less than half of the asset lifetime. In 2020, the potential FCR earnings were at a similar level as that of performing energy arbitrage, but with much less energy throughput and battery degradation. The Danish FCR prices peaked with a monthly availability payment above 350 €/MW.

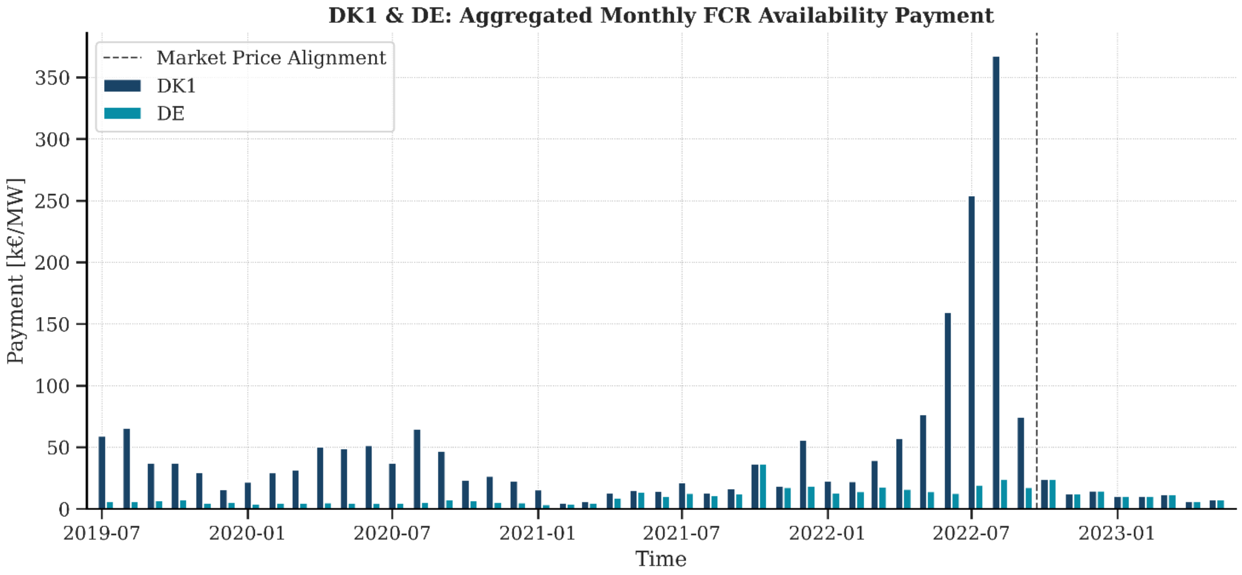


Figure 23 *Monthly revenue from reserve payment in the continental FCR market*

Table *12* shows the aggregated yearly capacity payment of all the ancillary service markets.

Table 12 *Yearly capacity (availability) payment per MW for different ancillary services (k€)*

	DK1			**DK2**				
Year	FCR (DK1)	FCR (DE)	mFRR	FCR-N	FCR-D Up	FCR D Down	FFR	mFFR
2019	354 k€	38 k€	8 k€	266 k€	176 k€	---	---	18 k€
2020	458 k€	64 k€	12 k€	149 k€	128 k€	---	180 k€	62 k€
2021	232 k€	156 k€	42 k€	325 k€	347 k€	---	476 k€	158 k€
2022	1127 k€	202 k€	12 k€	560 k€	522 k€	281 k€	497 k€	176 k€

3.5.7 Multimarket Bidding in DK2

The FCR services differ in revenues and energy throughput, and therefore in cost of delivery due to conversion losses and tariffs. Additionally, battery charge cycles reduce the usable energy capacity over time due to accelerated ageing. The FCR-N reserve had the highest availability payment in most of the past years, but comes with a higher energy throughput than FCR-D. By choosing the most profitable service in each hour, it is possible to increase profits of the BESS or EV-fleet. For each hour, the BRP can choose between either FCR-N, FCR-D Up + FCR-D Down or FFR + FCR-D Down, based on what gives the highest operational profit. For each hour, a BESS can be offered in one of the three service combinations. Hence, for each hour, the potential profit can be estimated based on price forecasts and expected cost of losses and tariffs (Engelhardt, Thingvad, Zepter, Gabderakhmanova, & Marinelli, 2023).

The cost of delivering FCR-D and FFR are negligible, while the cost delivering FCR-N is significant and amounts to 17-20% of the availability payment, depending on the grid connection type and the period. The cost depends on the hourly spot prices and tariffs, which changes each hour. The multimarket bidding algorithm was developed during the Alight project [12].

Figure *24* shows the yearly results of the optimal market allocation for a 1 MW /1 MWh BESS in DK2, considering the new LER requirements specifying that only 80% of the available power can be bid in FCR-D and only 66% for FCR-N. FCR-D Down was introduced in 2022 but assumed available and scaled with FCR-D Up for previous years. The BESS has 1 MW/1 MWh (usable) capacity, a roundtrip efficiency of 81% and a B-high connection with Radius Elnet tariffs.

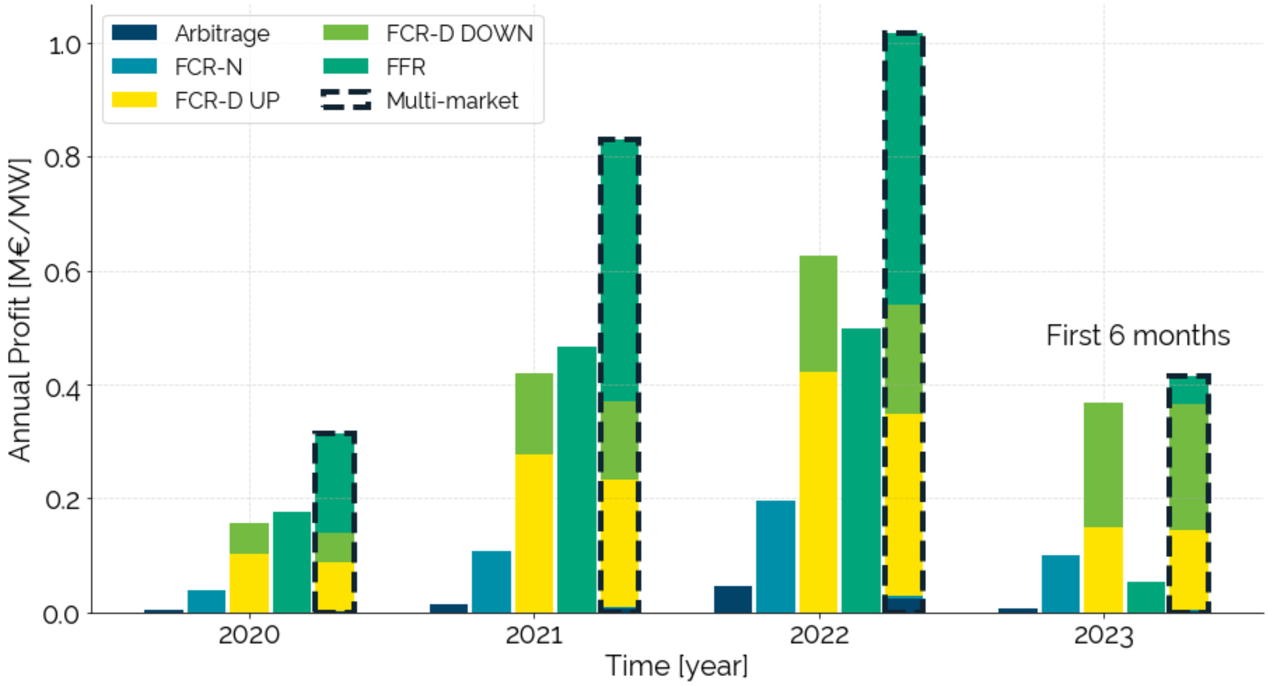


Figure 24 *Annual profit of delivering stand-alone services; Arbitrage, FFR, FCR-D Up + FCR-D Down and FCR-N, as well as the optimal combination of services*

The multimarket approach provides a larger pool of services to provide and larger potential revenue, thus being the best possible utilization of an asset for varying market conditions.

3.6 Parking Conditions and Flexibility Services

The parking conditions, or more specifically the parking duration, has a major impact on the feasibility of the different flexibility use cases. **Table *13*** gives an overview of the compatibilities of the various use cases with different parking durations. Some relationships are marked with a checkmark in parenthesis to highlight that it may depend greatly on the hour of the day or the forecasted demand.

Table 13 *Overview of parking duration compatibility with flexibility use cases*

Use Case	**Very Short-term Parking (< *30 min*)**	**Short-term Parking (½ - *2 hrs*)**	**Long-term Parking (2 – 24 hrs)**	**Very Long-term Parking (24+ *hours*)**
Peak shaving	(✓)	✓	✓	✓
Electricity cost reduction	✗	(✓)	✓	✓
CO_2-emission reduction	✗	(✓)	✓	✓
Energy arbitrage (*V2G*)	✗	(✓)	✓	✓
Ancillary services[1]	(✓)	✓	✓	✓

[1] The value of ancillary services is enhanced by V2G-capabilities.

It should be noted that assets with V2G-capabilities greatly enhance the value of ancillary services, since they are able to discharge energy to the grid, which means that a full battery does not necessarily imply that the asset is unavailable for subsequent bids into downregulating markets, since the battery can be discharged and then bid as downregulation capacity after a while. Furthermore, V2G also allows for the EV to not only be viewed as a consumer from a system perspective, but also a producer of energy. Thus, a fleet of V2G-chargers can deliver upregulation without setting a low charging baseline.

4 Provision of Ancillary Services with EVs – Case Study

The overview of flexibility sources presented in Section 3 indicated that provision of ancillary services is the most prominent value source from charging flexibility. Therefore, this case is further evaluated in the following section.

The response of consumers and producers is described in **Table *7*** of section 3.5. EV chargers are considered as consumers, since they are not expected to deliver power to the grid using the energy stored in their batteries. Therefore, upregulation using EV chargers is done by reducing consumption and downregulation is done by increasing consumption.

In general, EV chargers can provide frequency regulation when they are aggregated by an operator to provide a combined response in order to comply to minimum bid requirements. Since consumer behaviour is not controllable, bidding into the ancillary service market involves forecasting charging demand. When bidding into the market, it is possible to bid the 10th percentile of the forecast, implying that Energinet accepts deviation from an accepted bid for 10% of the time of the bid.

Since the bid consists of an aggregation of many assets, it is not a problem for a few EVs to be disconnected from the charger during provision of ancillary services. Energinet generally requires the measured response to be within +/- 2.5% of their requested response, with some additional details. Thus, as an example, a car or two disconnecting from a fleet of 200 active chargers will not be significant.

The simulation in this chapter assumes 100 EVs, each demanding 25 kWh consumption per day and equipped with a 11 kW AC charger. The AC chargers can only charge EVs (not discharge), hence the responses are provided by reducing or increasing power consumption. For this report, the focus is on an ON/OFF response, which is described in **Table *14***.
However, it is also possible for EV chargers to provide a response by modulating between a minimum and maximum charging current – typically between 6 and 16 A, equal to 4.14 kW and 11.04 kW at 230 V. A downside of this approach is that charging at lower currents often results in lower inverter efficiencies, which increases energy loss and ends up being more expensive for the customer, since they have to purchase larger amounts of electricity.

Table 14 *Basic combined ON/OFF response by a series of aggregated EV chargers*

System state	**Under-frequency**	**Over-frequency**
Activity	Upregulation	Downregulation
Required Response	Decrease consumption by 11 kW	Increase consumption by 11 kW
Response by EV Chargers	Turn off 1 x 11 kW Chargers	Turn on 1 x 11 kW Chargers

Market bidding requirements differ depending on the provided service. In the following sections and in a first step, the power and energy bids for various services of the illustrative example are established. Afterwards, the response of the system to frequency changes is illustrated for the 4-hour operational window and resulting charging time is calculated. Finally, financial performance is calculated for each of the market participation scenarios.

4.1.1 **EV Chargers & Ancillary Services**

In practice, EV chargers provide services that require lesser amounts of activation, which are:

- FFR, FCR-D and FCR-N in the Nordic Synchronous Area
- FCR in the European Continental Grid

When providing these services, the response is measured with respect to an operating baseline.

Table 15 *Response for symmetrical services with respect to an operating baseline for 100 chargers*

System state	**Under-frequency**	**Over-frequency**
Type of Service	Upregulation	Downregulation
Operating Baseline	550 kW (50 active chargers – 50 inactive chargers)	
Committed Capacity/Bid Size	550 kW	
Required Response[1]	Decrease consumption by 110 kW	Increase consumption by 110 kW
Response by EV Chargers	Turn off 10 x 11 kW Chargers	Turn on 10 x 11 kW Chargers
Measured Power	440 kW	660 kW

[1] Example value. The required response varies, as it depends on the measured frequency.

For symmetrical services, such as FCR and FCR-N, the operator needs to be able to increase and decrease consumption and is expected to react symmetrically (up and down) with the committed capacity. Assuming that a charging operator is charging 100 EVs using 100 charge points, they would need to charge 50 EVs while keeping the remaining 50 EVs on standby, so they can start charging on demand. When a response is needed, the operator will turn on or turn off the corresponding number of chargers to match the required activation power, as shown in**Table *15***.

For asymmetrical services, providing upregulation, (FCR-D Up and FFR) would require letting the EVs charge undisturbed for most of the time, while only turning them off occasionally, as shown in **Table *16***.

Table 16 *Response for up regulation services with respect to an operating baseline for 100 chargers*

System state	**Under-frequency**
Type of Service	Upregulation
Operating Baseline	1.100 kW (100 active chargers)
Committed Capacity/Bid Size	1100 kW
Required Response	Decrease consumption by 110 kW
Response by EV Chargers	Turn off 10 x 11 kW Chargers
Measured Power	990 kW

Providing downregulation, like FCR-D Down or as a part of symmetrical services, requires that the EVs are not charging, but are on standby and ready to start charging when required. Delivering FCR-D Down therefore conflicts with the general use case of public chargers that benefit from a high flow of energy.

4.1.2 **Providing FCR-N with EVs**

In operation, the response to the frequency deviations is achieved by turning ON and OFF more or less chargers to match required power activation, as shown in **Table *15***.

To illustrate this methodology, a simulation has been carried out for a fleet of 100 EVs, each having a charging demand of 25 kWh. With a baseline (operation at 50 Hz) of 50 EVs charging during the period of ancillary service provision, a full upregulating activation of FCR-N implies that all EVs chargers are switched OFF (0 EVs charging), while a full downregulating activation implies that they are all switched ON (100 EVs charging).

It is assumed that the total demand in the simulation is:

$$E_{\mathrm{demand}} = 100 * 25\ \mathrm{kWh} = 2.5\ \mathrm{MWh}$$

It is assumed that this demand is not distributed among the individual EVs, and the simulation is terminated once the total demand has been met. At any time, the charging power is equal to the number of EVs charging times 11 kW:

$$P_{\mathrm{charge}} = n_{\mathrm{EVs\ charging}} * 11\ \mathrm{kW}$$

The simulation time on 7 February 2021 is chosen arbitrarily from periods with significant frequency deviations in DK2 in 2021.

Figure *25* shows the result of the simulation, where system frequency and charging EVs are plotted against time. Providing FCR-N while charging EVs with ON/OFF control has a calculated charging time of 5.7 hours, compared to 2.3 hours for constantly charging at full power.

A capacity of 5.5 kW can be offered for FCR-N for 5.7 hours, if the EVs need to charge 25 kWh per day. A fleet of 100 chargers would offer 0.55 MW for FCR-N.

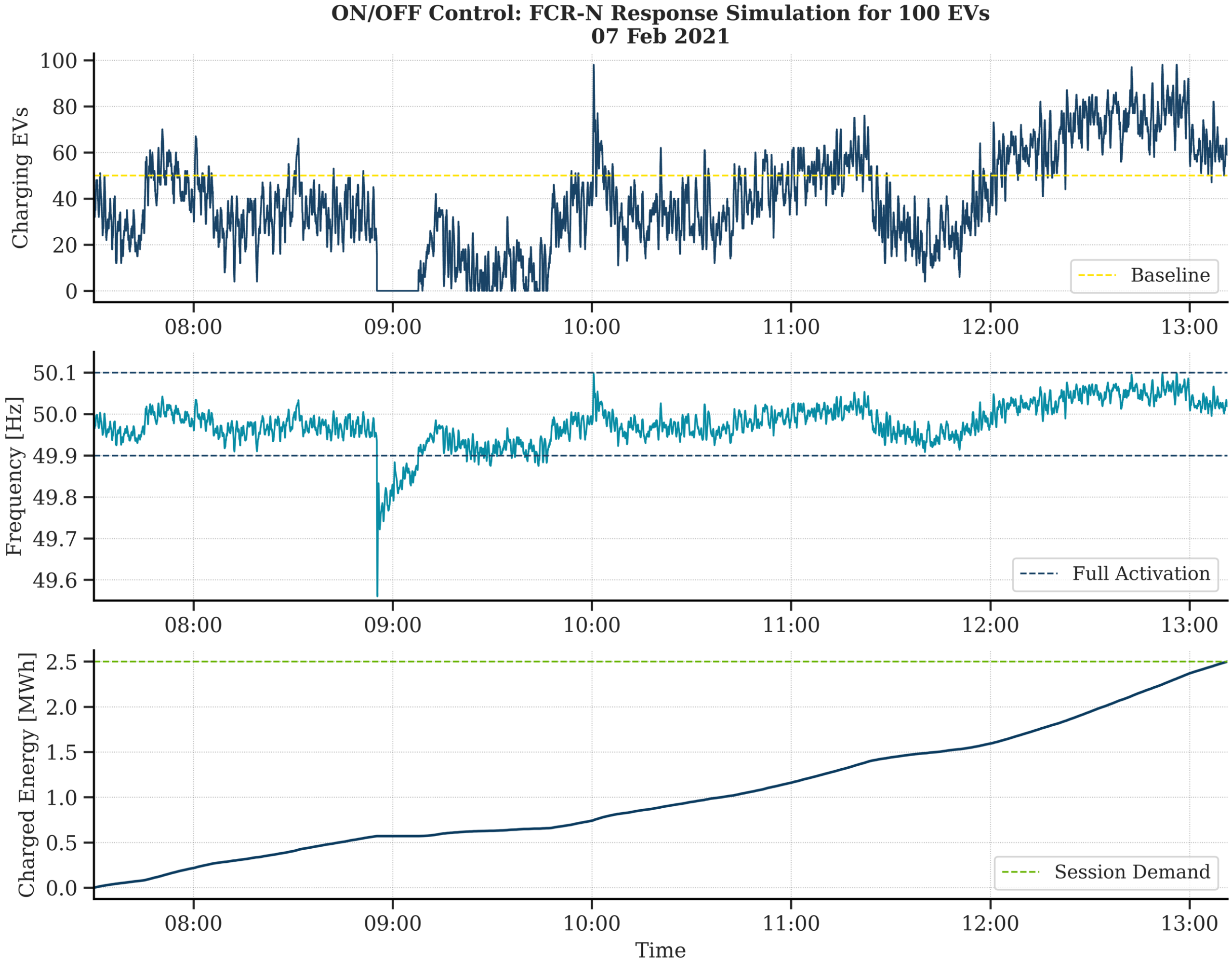


Figure 25 *Charger response for FCR-N services*

4.1.3 Providing FCR-D Up with EVs

The FCR-D Up & Down markets are the other primary reserve markets in the Nordic grid, which procure services for larger frequency deviation beyond the bounds of the FCR-N market and for significant disturbances in the grid.

The response required by the chargers for FCR-D Up is to turn OFF a number of EVs to provide upregulation in case of activation. The baseline is therefore all EVs charging at full power, providing a response whenever receiving a frequency measurement below 49.9 Hz. The number of chargers is determined by the frequency and requested upregulation power setpoint.

A similar simulation to the one in **Figure *25*** Charger response for FCR-N services is carried out for FCR-D Up for the same time sample. The resulting charging time is only about three minutes longer than the case of not providing any ancillary services. The results are given in **Figure *26***.

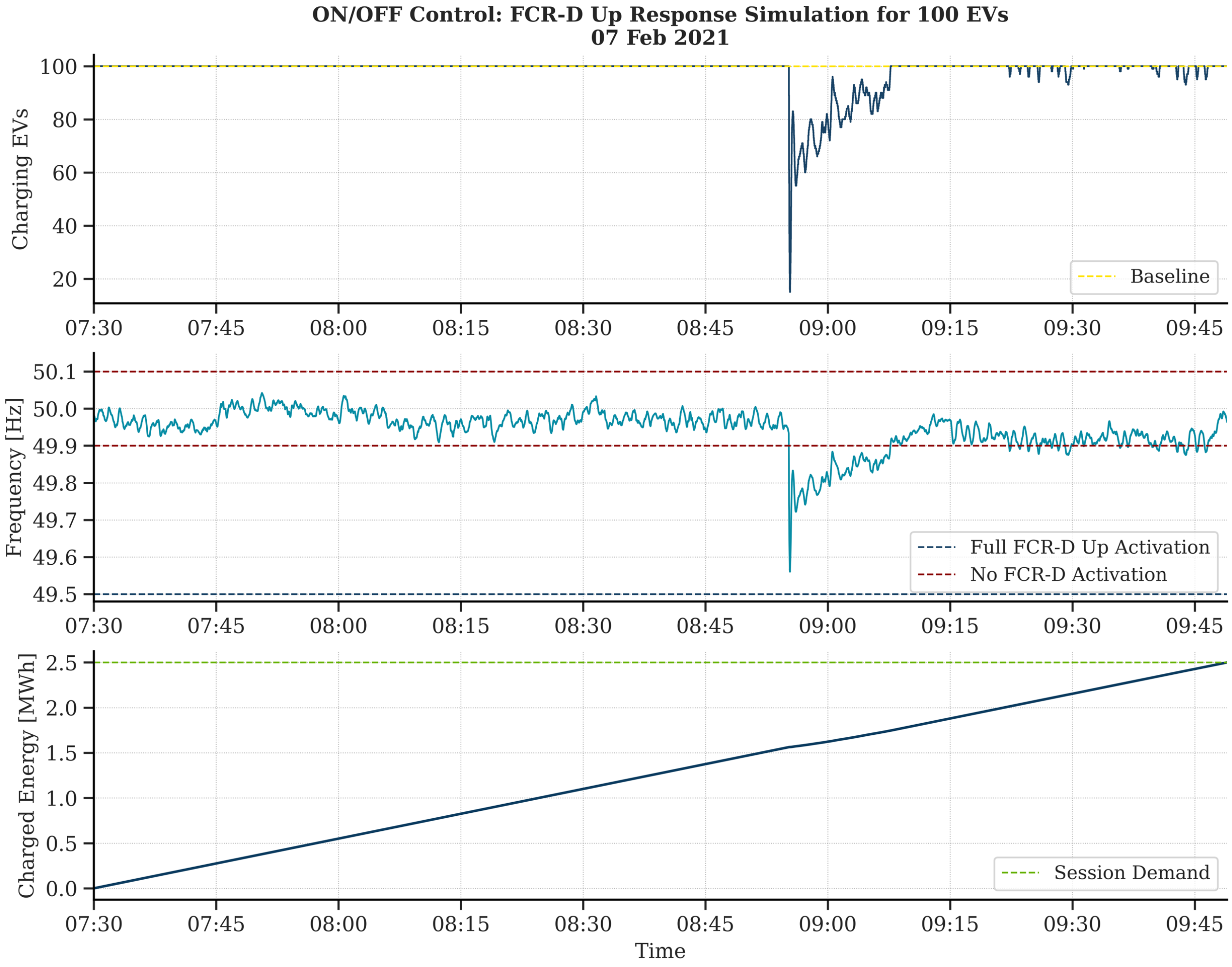


Figure 26 *Charger response for FCR-D Up services*

Charging EVs while providing FCR-D Up is simple, because a full power baseline of 1.1 MW (11 kW * 100 EVs) can be sold as upregulation. This response can be seen in **Figure *26***, where the number of EVs charging decreases when the frequency drops below 49.9 Hz. Providing FCR-D Up generally only increases charging time by a few seconds or minutes. Hence, this market is perfect to deliver charge to EVs while providing grid services.

A capacity of 1.1 MW can be offered for FCR-D Up for 2.3 hours, if the EVs need to charge 25 kWh per day.

4.1.4 Providing FFR with EVs

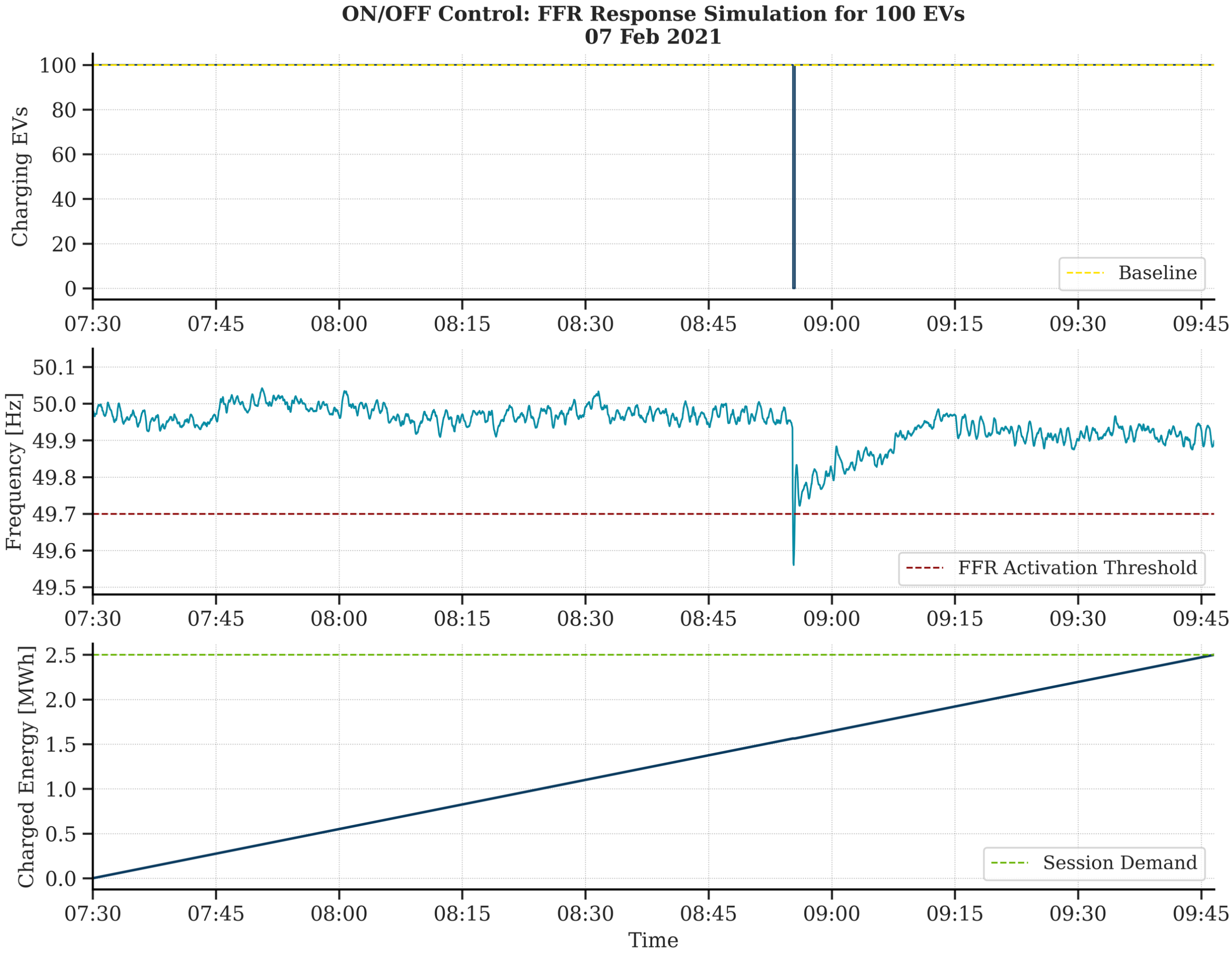


Figure 27 *Charger response for FFR services*

As seen in **Figure *27***, the charging process is largely unaffected by provision of FFR, only affecting the charging duration by a few seconds. If the assets can fulfil the speed requirements for responses, FFR is a good option due to its low activation and low energy content. However, the amount of FFR reserve purchased is much more limited than FCR-D, and the revenue flow is less stable.

4.1.5 Providing FCR with EVs

Providing FCR with EVs is very similar to FCR-N, except the activation is much smaller in magnitude.

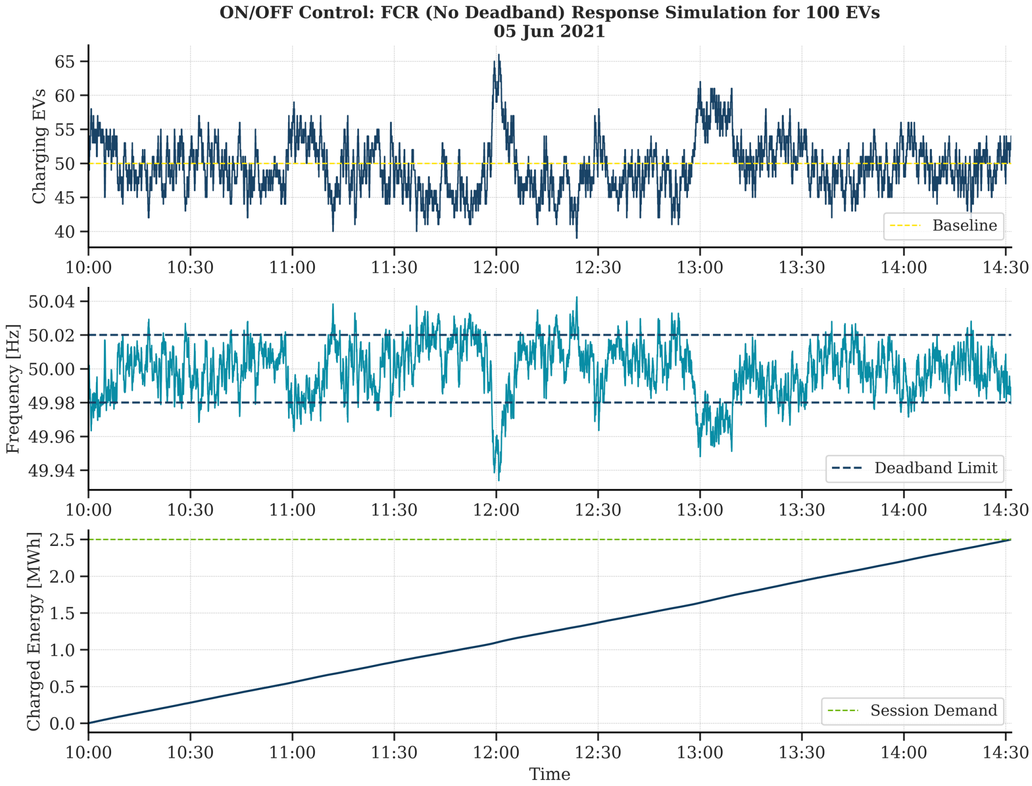


Figure 28 *EV chargers delivering FCR (no deadband) service when charging*

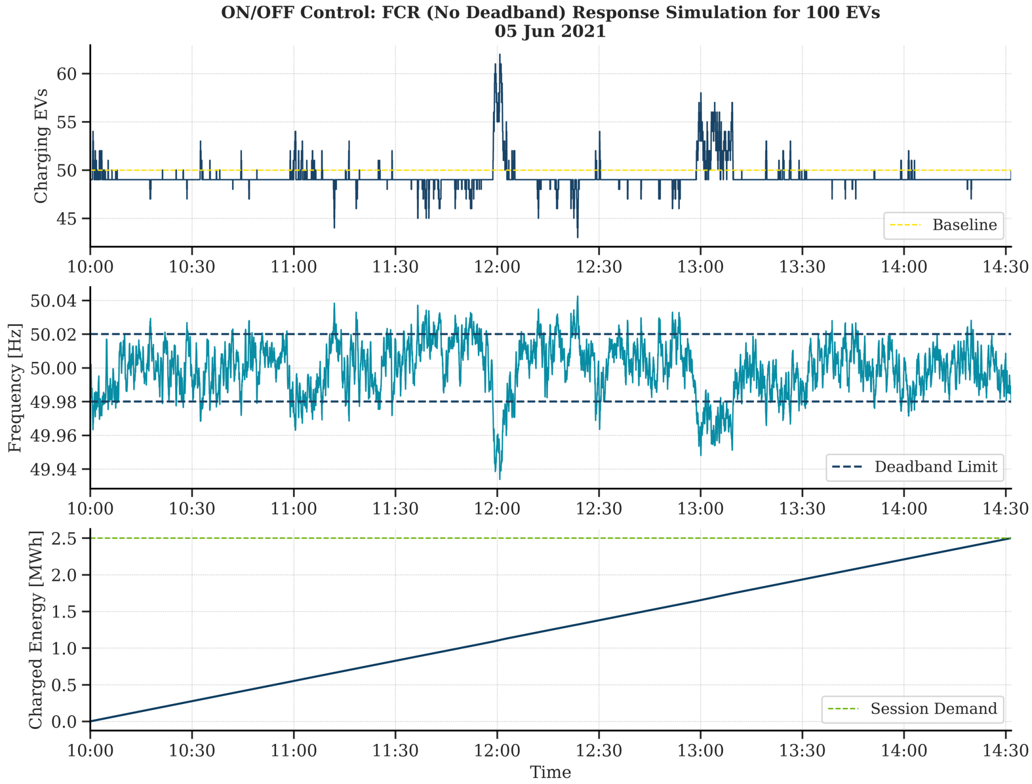


Figure 29 *EV chargers delivering FCR (with deadband) service when charging*

A total of 50 EVs will be charging most of the time while the frequency is between 49.98 Hz and 50.02 Hz. The effect of the deadband can be seen in the **Figure *28***. Like FCR-N, the EV charging time for FCR increases greatly to 4.53 hours.

A capacity of 5.5 kW can be offered for FCR for 4.53 hours, if the EVs need to charge 25 kWh per day.

4.1.6 Simulation Summary

A summary of the simulation for the services provided in DK2 is given in Table 17, while a summary for the FCR service in DK1 is given in Table 18.

Table 17 *Simulation summary (DK2) – time sample from 7 February 2021*

	Base	FCR-N	FCR-D Up	FFR
Simulated Sample Charging Time [minutes]	135.88	341.45	138.98	136.6

Table 18 *Simulation summary (DK1) – time sample from 5 June 2021*

	Base	FCR	FCR (Deadband)
Simulated Sample Charging Time [minutes]	135.88	271.65	271.61

4.1.7 Economic Value of Delivering Ancillary Services

The limiting factor for earnings from EVs delivering ancillary services is their energy demand as it limits the charging time. An EV in Denmark consumes on average 10 kWh per day, which means it could deliver FCR-N or FCR for two hours per day or FCR-D for one hour per day [13]. Public chargers in Denmark on average deliver 32 kWh per day, corresponding to three times the daily energy consumption of a single car [14].

Table 19 *Average annual revenue from a single 11 kW AC charger charging 25 kWh per day*

Service	**FCR-N**	**FCR-D Up**	**FCR DK1 (DE prices)**
Capacity	**5.5 kW**	**11 kW**	**5.5 kW**
Duration	**4 hours/day**	**2 hours/day**	**4 hours/day**
2019	244 €	161 €	325 €
2020	137 €	117 €	418 €
2021	298 €	318 €	214 €
2022	513 €	479 €	185 €

Table *19* shows how much a single 11 kW AC charger can earn annually based on historical data, meeting a demand of 25 kWh every day for 365 days. 2 to 4 hours is needed to charge the EV while simultaneously providing an ancillary service.

Considering the high annual revenues and minimal effect on charging duration, FCR-D Up is a good fit for public EV chargers. It is possible to provide FCR-D Up and Down at the same time, but this requires a lower baseline setpoint to allow for frequency down-regulation (increasing EV charging), thus increasing charging time. In the case of EVs plugged in for longer duration charging with no requirement for a speedy charging process, FCR-N and FCR provide good passive income at the cost of roughly doubling the charging time. Likewise, a multi-market bidding strategy can greatly improve the business case of providing ancillary services with these EVs.

5 Roles and Responsibilities

The successful implementation of flexibility and ancillary services for EVs is dependent on collaboration between EV owners, charging infrastructure owners, electricity suppliers, aggregators, and charge point operators. This section presents the roles and responsibilities of each of these parties in creating a seamless charging experience for EV drivers while utilizing all the potential use cases of smart charging, ancillary services and V2G. Some flexibility use cases can be performed with a local controller, while others require market participation by a balance responsible party or balance service provider.

Whether or not the approval of the EV owner is necessary for these use cases depends on a service contract made with the charge point operator (CPO). Depending on the owner structure and which services are to be provided, there may be conflicts of interest.

A service contract also states whether the approval of the charging infrastructure owner is necessary. If the CPO is not the owner of the infrastructure, this can present conflicts of interest, but it is not necessarily a dealbreaker – especially in the case of providing low energy content services, such as FCR-D, which have a small magnitude of activation.

Figure *30* presents an overview of the actors involved in the provision of ancillary services to the grid. Smart charging and V2G operation do not require involvement of aggregators, balance responsible parties or balance service providers. It is mostly dependent on agreements between the electricity supplier and the CPO. Further information about the actors is given in the following subsections.

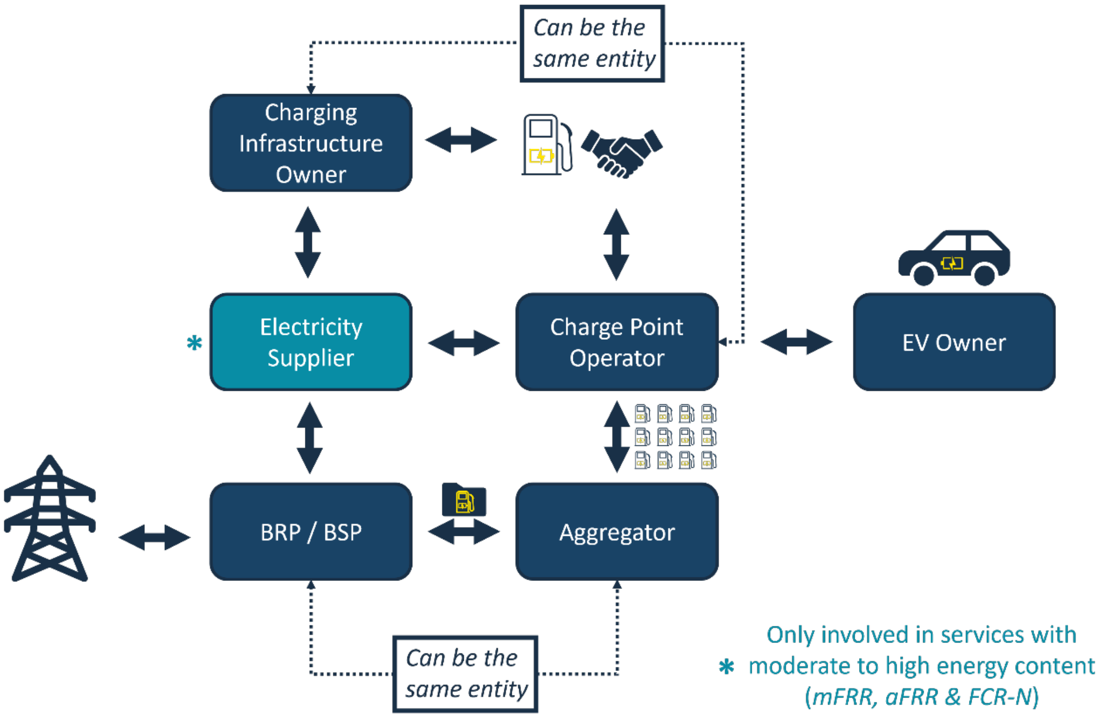


Figure 30 *Illustration of the different actors involved in the process of using EVs for ancillary services*

5.1 Charge Point Operator

The Charge Point Operator (CPO) is the entity in direct contact with EV owners and is responsible for operating and maintaining the charging infrastructure. The CPO has a financial incentive to optimize the utilization of the chargers, which can be achieved by increasing the number of charging sessions per charger per day and increasing the duration of each charging session.

While simultaneously increasing the potential for providing grid flexibility, the utilization of the charger can be increased by:

- Offering incentives for smart charging at off-peak times
- Encouraging the use of lower power outputs in areas of less frequent and less time-intensive charging demand

The CPO may also have an environmental incentive to optimize the utilization of the chargers, by encouraging EV owners to charge their vehicles at times when the electricity mix is cleaner.

5.2 Charging Infrastructure Owner

The charging infrastructure owner has a responsibility to ensure that the charging infrastructure is safe, reliable, and accessible to all EV owners. They must also comply with relevant regulations and standards for electric vehicle charging. By providing a high-quality and reliable charging experience, the charging infrastructure owner can enhance the overall satisfaction of EV owners and encourage greater adoption of electric vehicles.

In many cases, the CPO is also the owner of the infrastructure, but this is not the case for all CPOs.

5.3 Balance Responsible Party

The suppliers must ensure that production and consumption of electricity are always in balance with the traded energy in the spot market and may be required to pay fees or receive rewards for imbalances. This is referred to as balance responsible party (BRP) which has access to sell balancing energy and reserve power capacity to the TSO and, when possible, the DSO.

A BRP is a legal entity that can and may handle the balance responsibility for production and consumption units and/or trades physical power. Because this role gives access to both the day-ahead market, intra-day market and the balancing market, a BRP can be active in both the electricity market and the balancing market. The BRP is financially responsible for imbalances and deviations between the planned and the actual production, consumption, and trade of power. A BRP can also, through agreement with Energinet, deliver ancillary services, if the technical and legal requirements are met.

5.3.1 Balance Service Provider

A more recent addition to the system, the balance service provider (BSP) does not have access to the regulating market but is able to participate in low energy markets (FCR, FCR-D and FFR) for reserve capacity with an approved portfolio, which has passed the pre-qualifications specified by the TSO.

5.4 Aggregator

An aggregator is exclusively responsible for changes in consumption and production through control and regulation of one or more installations and therefore not necessarily affiliated with the customer's supplier. The role of an aggregator is to facilitate the participation of small loads, like chargers, in the balancing of the electricity grid. This is why the role is commonly referred to as a demand side-flexibility aggregator [9].

An aggregator has contractual obligations with the customer that specify the terms for the adjustable energy consumption or production. In that regard the aggregator must comply with all applicable trading and balancing rules. This includes, among others:

- Customer payment for delivered flexibility service
- Customer access to information about the adjustable consumption or production

The aggregator is financially responsible for flexibility activation and may also be responsible for the rebound effect, which is the energy that the flexibility activation will give rise to, typically outside the activation window. Any imbalances resulting from the aggregator's flexibility activation will be adjusted by a central entity, such as the TSO. The legal framework, Electricity Directive (EU) 2019/944, to sell explicit flexibility to the TSO through an aggregator is in place in some countries, but the technical implementation is still missing for system services that require balance responsibility.

The aggregator and the BRP (or BSP) can be the same entity.

5.5 Electricity Supplier

The supplier is responsible for selling or purchasing electricity and must adhere to all applicable trading and balancing rules. This includes:

- Collecting payments for energy, transport, and taxes
- Paying for generated production
- Being financially responsible for any imbalances or delegating this responsibility

Electricity contracts in Denmark can have either fixed or dynamic prices. With fixed price agreements, the supplier and customer agree on a set price for the duration of the contract, and the supplier takes on the risk of price fluctuations. Dynamic price agreements allow the customer to choose a price that follows the marginal price of the day-ahead market, plus a markup or a subscription fee. Thus, the customer takes on a larger share of the risk for price fluctuations, but also the benefits from the flexibility of the consumption.

The electricity supplier also has a close connection to the BRP, since the BRP has the financial responsibility for the stability of the grid. Thus, the BRP serves as the link between the electricity supplier and the grid when purchasing (consuming) electricity.

5.6 Connecting the Dots

In summary, the process of using EVs for flexibility services, and especially ancillary services, involves a lot of actors and regulations. While smart charging and V2G may be easier to implement from a regulatory perspective, there is often great financial incentive for providing ancillary services to the grid, and with the involvement of an aggregator and BRP/BSP, especially if they are the same entity, the process is not much further complicated from the perspective of the CPO or infrastructure owner.

The aggregator would usually be handling a portfolio of many different assets from the CPO and sell their combined flexibility to the BRP, which then sells it to the TSO, but they do not necessarily have the detailed information about every asset.

Providing ancillary services with EV chargers involves the following main steps:

1. Forecasting of charging demand
2. Measurement of frequency and evaluation of frequency response
3. Turning chargers on or off (in the case of ON/OFF-based control)

The aggregator can get direct access from the CPO to switch assets on or off, and as such they may carry out all three steps. Step 1 and 3 can be done by both actors, while the second step is handled by the aggregator. As such, close cooperation between aggregator and CPO is required for provision of these services. An overview is given in **Figure *31*** and **Figure *32***.

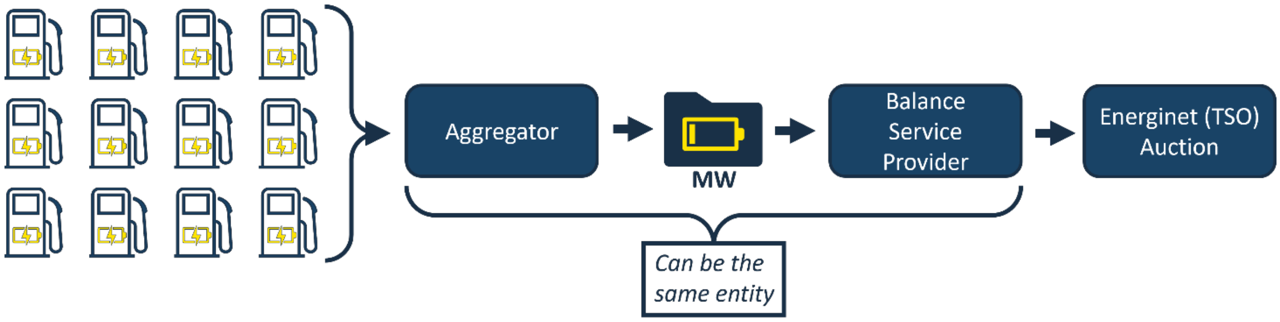


Figure 31 *Illustration of main actors in providing low-energy (reserve capacity) ancillary services (FCR, FCR-D & FFR)*

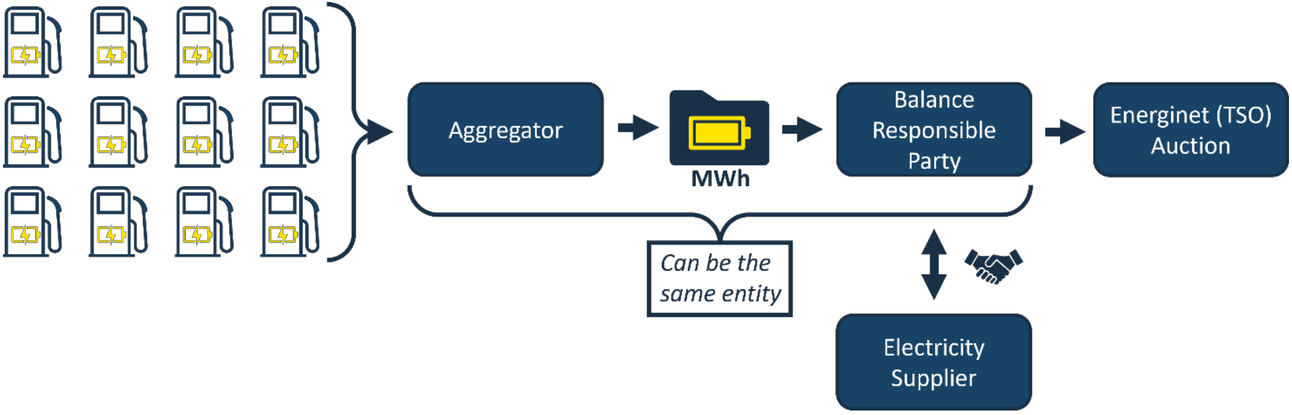


Figure 32 *Illustration of main actors in providing high-energy ancillary services (mFRR, aFRR & FCR-N)*

5.6.1 Multiple Actors and Asset Response Times

Providing ancillary services involves strict response time requirements specified by the TSO for the varies types of services as presented previously in **Table *8***. Most EV chargers utilizing OCPP for communication have been proven to fulfill these requirements. Some chargers use a proprietary API for controlling their chargers via a virtual OCPP-connection, which gives an additional time delay that can potentially be prohibitive. It is therefore highly recommended to use chargers controlled via OCPP.

The speed of the signal flow between asset and aggregator is also not without importance. The signal must always pass through the CPO's backend, and as such the flow through the backend must be optimized for speed. This can be done within the range of tens of milliseconds, an order of magnitude which has little to no influence on the ability of the assets to fulfill the requirements for response speed.

5.6.2 Ensuring Sufficient State of Charge for EV Owners

Figure 33 *EV owner satisfaction*

Availability of the EV for driving purposes after charging is the main concern of the EV owner. None of the smart use cases are feasible if the owners end up dissatisfied with the charging experience. Thus, an adequate SOC must be ensured at the end of the charging period.

This is of little concern in the case of ancillary service provision with low energy content but very relevant in the case of load shifting, smart charging and V2G applications, as well as high energy content ancillary services. In these cases, the charging operation is controlled by the CPO or the aggregator within constraints specified by the parking conditions. This also has an advantage when forecasting available capacity for flexibility services, because the baseline will be known. The constraints will vary for long-term parking, short-term parking and employee parking, but they will always have EV owner satisfaction as an objective.

6 Conclusion

The Alight project at Copenhagen Airport aims to leverage smart charging and vehicle-to-grid (V2G) technologies to utilize EVs as electrical flexibility assets in multiple ways. The project involves demonstrating the integration of smart charging and V2G with a smart energy management system to optimize renewable energy absorption, manage consumption, and alleviate potential grid congestion.

The key aspects and potential benefits of implementing smart charging and V2G are as follows:

Reduction of CO_2-emissions and Electricity Costs: By shifting EV charging to hours with the lowest electricity prices or CO_2-intensity, the project can directly contribute to reducing both carbon emissions and electricity expenses. This simple implementation of smart charging can be achieved by adjusting charging power during different pricing periods. This can also result in reducing grid congestion due to its correlation with prices and CO_2-intensity.

Value Creation through Information Exchange: If the plug-out time and energy demand of EVs can be forecasted at the plug-in time, the charge controller can optimize charging schedules to align with the lowest electricity prices. This requires more information exchange with EV users but can lead to increased value and cost savings.

Ancillary Services and Revenue Generation: The charge-controller can create an additional revenue stream by selling the power capacity of EV chargers to the transmission system operator (TSO) as ancillary services. These flexible power capacities can be activated to help maintain the power balance in the grid, providing services such as Frequency Containment Reserves for Normal Operation (FCR-N) and Frequency Containment Reserves for Disturbances (FCR-D).

Supporting low-Emission Mobility: The report highlights that the growing adoption of EVs presents an opportunity to reduce carbon emissions in the transportation sector. Smart charging can play a role in supporting this shift to zero-emission mobility and contribute to a more flexible power system with increased renewable energy integration.

Overall, the white paper aims to provide owners of parking houses with valuable information to make informed decisions when establishing EV charging infrastructure at large parking facilities like Copenhagen Airport. The adoption of smart charging not only brings economic benefits and carbon emission reduction but also supports the transition towards sustainable and environmentally friendly transportation.

The report provides a solid foundation for utilizing smart charging and V2G technologies in parking facilities. However, it is important to note that successful implementation would also require considering various factors such the EV owner's willingness to participate, data privacy concerns, and the coordination with the other stakeholders to ensure smooth integration into the power grid.

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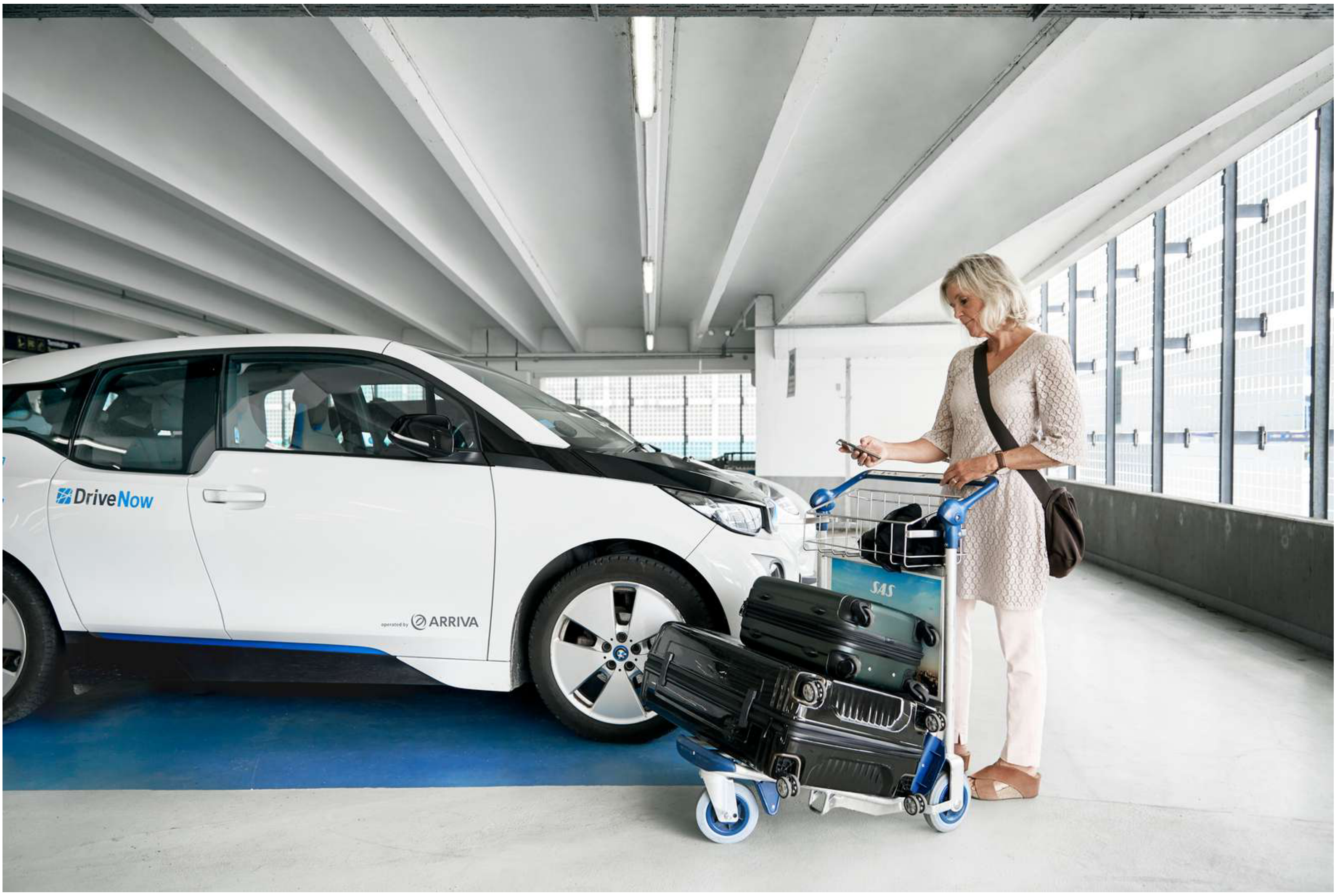

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