Ea Energy Analyses

# The value of electricity storage

## An outlook on services and market opportunities in the Danish and international electricity markets

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# Foreword

Elsystemansvar A/S (subsidiary of Energinet) has asked Ea Energy Analyses to analyse the benefits and main drivers for the installation of storage units in the Danish power system. This will supplement the technology aspects in the recent Technology Catalogue on Energy Storage (DEA and Energinet, 2019).

The analysis covers both services that are already reflected in a market structure and services that are (not yet) monetized. Short-term perspective is considered, that is opportunities arising between 2020 and 2025. The focus is on transmission grid applications, though in some instances opportunities in the distribution grid are mentioned.

# 1 Executive summary

Electric storage has experienced a growing interest in the last years due to a general cost drop, its manifold potential applications in the energy sector and a wide array of technological options. The attractiveness of electric storage is motivated by its ability to provide multiple grid-related and market services, as a response to an expected increase in the demand for system flexibility from new suppliers as the number of traditional suppliers decline.

This report introduces the pivotal technical features of three promising storage technologies (batteries, flywheels and thermal storage) and highlights their suitability to create value from flexibility and provide system services. Through an analysis of demonstration projects, pilot installations and literature findings the role of storage is reviewed and discussed in both the Danish and the international context.

Several demonstration and commercial projects have been carried out worldwide[1]. Batteries are the storage type with the most far-reaching applications; among them, Li-ion technologies have gained a remarkable attention due to their technology readiness level and a sizeable cost reduction in the past years.

Batteries (and – more generally – storage) can in fact create value from flexibility and provide a set of different services in power systems and potentially combine them into a single business case. Applications include energy-only market activities such as arbitrage and system balancing but also a series of grid-supporting services (frequency and voltage regulation, system reliability, grid investment deferral).

After going over the main features of the Danish electricity markets – with a focus on the provision of ancillary services – opportunities for value-stacking (utilizing opportunities across markets) are identified and examined for the year 2025 at the transmission grid level. As a starting point, storage is found to be most competitive in markets providing small but high value products, asymmetrical bids and/or a short temporal scope. The market most suited for electricity storage is FCR (primary reserve), while other markets such as aFRR (secondary reserve) and day ahead spot markets may contribute to the income of a storage unit. In practice, we find that the opportunities for value-stacking in a Nordic/Danish context are limited due mainly to the following

[1] For a comprehensive list of battery projects see Sandia. Last accessed: March 2020.

circumstances: Value-stacking cannot be achieved without accepting risks and competition, as is the case with any provider of ancillary services. Additionally, some services are not yet exposed to the market, and cannot be delivered by commercial providers of flexibility[2]. Finally, a well-integrated Nordic system entails a market with more providers and thus stronger competition. The analysis is based on projected prices in the day-ahead market and current prices in the frequency reserves markets. The analysis does not cover all the potential business cases for revenue-stacking but identifies major drivers and contexts where storage – and batteries in particular – can be of relevance in the power system.

The analysis finds that:

**Participating in the day-ahead market and, more generally, in energy-only markets does not constitute a viable business case for storage today or in the near future**. While the system deployment of storage is strongly linked to its spread in the energy-only markets (where most trading activities take place), this is unlikely to happen in the very short-term. Further cost cuts and reduced degradation over time will be key for this opportunity to materialize.

**The participation in the ancillary service markets is attractive for storage technologies, as they satisfy the markets technical requirements and can access availability payments**. These markets are growing in number and size in Denmark in the coming years, starting from the introduction of a Fast Frequency Response Market in DK2 in late 2020. Flywheels and batteries have response times and features adequate to FCR (primary reserves) and/or aFRR (secondary reserves). An asymmetric market design that allows suppliers to only deliver up regulation (as it is today in DK1) is found to be attractive.

**The limited potential of storage highlighted in previous Danish demonstration projects is a result of design choices and particularly of small volume-to-power ratios for batteries.** While underlining the suitability for frequency ancillary services, batteries in the Nordhavn and Lem Kær projects were designed with limited volumes and higher power components. Investment costs for expanding a unit's volume have fallen rapidly and the ability to store energy is key to provide frequency support without incurring penalties.

[2] Whenever, the need for a system service not covered by existing markets are identified, new solutions are investigated by the Nordic TSOs (Energinet, Fingrid, Statnett & Svenska kraftnet, 2020).

**The Danish FCR (primary frequency reserve) markets offer a positive business case for Lithium-Ion batteries in 2025, with Internal Rates of Return over 10%**. This finding applies to both DK1 and DK2, despite differences in the regulation and under the hypothesis of stable market prices. Successful introduction of batteries in these markets may reduce the revenue.

**Combination of different markets are possible; however, the limited storage capacity creates challenges.** A storage unit optimised for the day-ahead market will typically have two full cycles per day. This means that the storage unit will be empty and filled twice a day. Delivering in other markets, e.g. regulating power, may create imbalances as planned delivery may not always be possible in the periods with a full or empty storage. This challenge is unique to storage technologies, because of limited storage capacity.

Overall, the integration of storage facilities in the ancillary services markets would lead to a limited deployment of such technologies in the power system. The aggregate demand for FCR (primary) and aFRR (secondary) reserves in Denmark total 83 MW and 110 MW respectively in 2020. Hence, the volumes in the ancillary service markets are comparatively minor in size and is likely to saturate quickly, thus leading to self-cannibalisation of storage technologies; therefore, business cases based on today's prices should be interpreted with caution. Moreover, the services that dedicated storage can provide may come from other sources in the future: for instance, solar and wind power, electric vehicles, electric heat pumps and electric boilers in district heating or for individual heat supply (Ramboll, 2019). .

As a large deployment of storage is linked to the participation in the energy-only markets, it is recommended to continue the focus on  the development of regulations and market rules which support a level playing field where both mature and novel technologies – including storage technologies - may compete under fair and transparent conditions.

# 2 Motivation

Storage costs have declined consistently in the past years; while the storage family is rather big and heterogenous, some options have witnessed learning rates comparable to those of photovoltaics and wind energy; for instance, Li-Ion batteries' learning rates has been recently estimated to 18% by Bloomberg (Bloomberg, 2019) and Redox-flow utility batteries' learning rates to 13% (Louwen, Junginger, & Krishnan, 2018). In other words, the price of a Lithium-Ion battery was 1,000 $\$_{2017}$/kWh in 2010, but it is expected to cost less than 100 $\$_{2017}$/kWh by 2025 (DEA and Energinet, 2019). This cost reduction opens up new and widespread opportunities for large scale applications in the power sector.

In 2019, wind generation in Denmark supplied 47% of the electricity demand and solar power added another 3%. Additional wind and solar capacity is underway. The variability of this generation is a challenge to be managed cost-effectively.

The deployment of storage could potentially support both grid management (quality and stability of power grid parameters) and the market flexibility (matching of supply and demand). In the first case, storage can help to preserve the power grid by providing ancillary services including voltage support; moreover, storage units are expected to be used as black start unit. In the second case, storage can contribute to balancing the system and potentially lowering the total system costs when and if they become competitive to other means of flexibility and balancing.

The interest in storage technologies is also motivated by the progressive phase-out of units traditionally providing a set of ancillary services, e.g. FCR (primary reserve) and voltage regulation. These are large power plants often fired by fossil fuels and biomass, now being disposed of in favour of renewables. Quality and quickness of the response to system signals are also increasingly valued. However, storage is not the only new technology able to provide ancillary services and the specific investment case will influence the competitiveness of different technologies. (Ramboll, 2019)

For these and other reasons outlined in the following, storage holds a vast potential in manifold power sector applications, such as flexibility and ancillary service, which can materialise in the upcoming years.

# 3 Storage technologies

This Chapter introduces the types of energy storage considered in this study: Li-Ion batteries, flywheels and high-temperature thermal energy storage (HT-TES). A first distinction is made between units characterised by predominantly an energy or a capacity component: this broad classification already suggests the potential use in the markets and is also closely related to another possible grouping, i.e. short- and long-term storage. The latter distinguishes between units with different energy components (volume), that is the duration of the discharging time at full capacity. Other important technical features are listed below:

Power, capacity and energy applications

Storage can be employed for power and energy applications (SANDIA, 2010). In the first case, the unit is required to have a fast response and typically for a limited amount of time (seconds to minutes). In the second case, long discharge times at full capacity (up to several hours) are required. Power applications fulfil their role in short time spans and can restore the desired state of charge (SOC) relatively fast. On the contrary, energy applications demand longer discharge times and a continuous service, mostly to ensure reliability or to comply with the market design.

Short-term storage

Batteries and flywheels are considered short-term energy storage technologies. Batteries represent a wide variety of solutions which can be grouped into two classes: flow and solid-state batteries. Depending on the specific electrode and electrolyte they have gained different maturity levels and are characterised by slightly different technical parameters. Lithium-Ion batteries can reach round-trip efficiencies of over 90% (DEA and Energinet, 2019) and have been tested in demonstration and commercial projects in Denmark and abroad (Table 1). Flywheels have also reached commercial status; they can fulfil the same functions as most types of batteries. Flywheels make use of reversible electric machines that act as a motor/generator in the loading/unloading phase: electric energy is converted into rotational kinetic energy with round-trip efficiencies above 80% (EERA, 2016) but self-discharge losses in the order of a few percent per day (DEA and Energinet, 2019).

Long-term storage

High-Temperature Thermal Energy Storage (HT-TES) provides an option for long-term storage (Ea Energy Analyses, 2019). As of 2019, HT-TES has not reached commercialisation, but several companies and research projects are focusing on improving the technical efficiency and the economics[3]. Two

[3] See for instance Siemens ETES.

different charging concepts have been studied (Lo Brutto & Pérez, 2017): through a heat pump or an electric heater; the discharging occurs via a traditional Ranking cycle or through a Brayton air cycle. The latter is dependent on the TES temperature level, which is roughly 600°C. Heat is for example stored in rocks.

| | Location | Primary usage | Year | Capacity |
|---|---|---|---|---|
|  | Energylab Nordhavn, Copenhagen, Denmark | Frequency Regulation<br>Peak Shaving<br>Voltage Regulation | 2017 | 630 kW<br>460 kWh |
|  | Lem Kær Wind Farm, Denmark | Frequency regulation | 2014 | 1.2 MW / 300 kWh<br><br>0.4 MW / 100 kWh |
|  | Mira Loma Substation, California, USA | Peak Shaving | 2016 | 20 MW<br>80 MWh |
|  | Neoen's Hornsdale Wind Farm, South Australia | Peak Shaving | 2017 | 100 MW<br>129 MWh |
|  | Laurel Mountain, West Virginia, USA | Frequency Regulation and Renewable Energy Integration | 2011 | 32 MW<br>8 MWh |

*Table 1. Examples of Lithium-ion batteries projects (DEA and Energinet, 2019).*

Main technical parameters

Table 2 summarises the main technical features of storage facilities. These mark the type of service a unit can provide from both a technical and regulatory point of view. The reference technology for batteries is the Li-ion type; technical parameters vary for the other concepts. HT-TES is still under demonstration and its technical lifetime depends on both the charging and discharging modes as well as on the ability of rocks to endure multiple cycling. Thermal gradients and stress on the insulation material reduce the storage lifetime.

Lifetime is often not as explanatory as the number of cycles a unit can endure; this is particularly true for batteries. Several studies investigating the market potential of batteries report a remarkable ageing when providing frequency regulation, which often more than halves the expected lifetime (see for instance (Yao Meng, 2019)). In practice, the lifetime of certain storage units (electrochemical storage) is heavily dependent on the depth of discharge, as shown in Table 2. In the event of full charging and discharging cycles, batteries last up 4 times less than flywheels and usually at a loss of efficiency (TERNA, 2018). On the contrary, flywheels are supposed to ensure a stable performance throughout their lifetime and a negligible ageing.

| Technology | Lifetime [years] | N° of cycles [-] | Response time [s] | Discharge time [hours] | Round-trip efficiency [%] |
|---|---|---|---|---|---|
| Batteries | 20[4] | $10^4$ | 0.008 | < 6 | > 90% |
| Flywheels | 20 | $10^6$ | 0.003 | < 1 | > 90% |
| HT-TES[5] | 20 | - | High | Up to a day | > 25%[6] |

*Table 2. Typical technical features of the different energy storage technologies.*

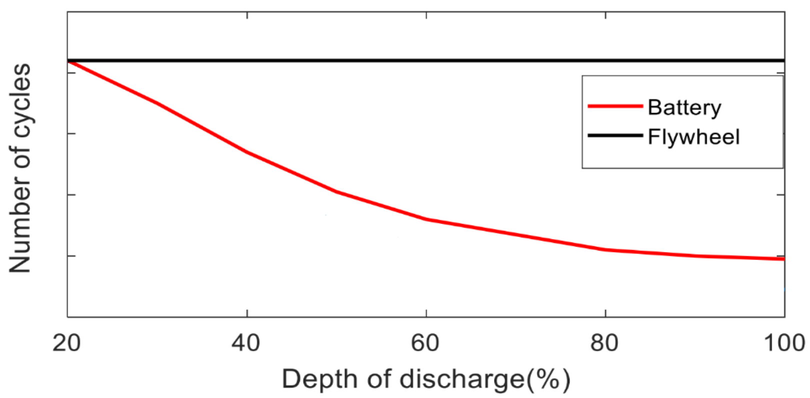


*Figure 1. Schematic illustration of the lifetime of batteries and flywheels as a function of depth of discharge. Elaboration from: (Yao Meng, 2019).*

[4] The lifetime is strictly dependent on the type of application and the number of cycles per year.
[5] Data is for the ETES (Electric Thermal Energy Storage) developed by Siemens.
[6] Electric-to-electric. The efficiency is projected to increase up to 50% according to Siemens (Lo Brutto & Pérez, 2017).

# 4 Markets, drivers and barriers

The evolution of the electricity markets and of the grid development, demand and generation fleet brings about a wide set of system needs and opportunities. The following subsections review the drivers that make the participation of storage into existing or potential markets attractive.

## 4.1 Drivers for storage deployment

Phase-out of conventional generation

The ambitious climate targets drive the phase-out of fossil fuel power plants. Unlike Variable Renewable Energy Sources (VRES), thermal power plants are synchronous with the system and have traditionally provided a number of ancillary services. Their shelving opens up opportunities for new technologies including energy storage (Ramboll, 2019). Moreover, conventional generation is particularly subject to wear and tear when providing ancillary services that require a fast response (SANDIA, 2010).

Flexibility needs

The deployment of VRES, , needs to be paired with flexibility measures. These have traditionally included the broadening of thermal generators' operational ranges and the strengthening of the transmission grid. Storage can also be flexibility provider and thus potentially help the integration of VRES and reduce the amount of curtailed VRES. Synergies can be identified also with other flexibility providers, such as cross-regional interconnection capacity.

Prices and price spreads

Due to different product definitions and quality, market designs, traded volumes and participating technologies the remuneration of system services spans over relatively wide ranges; therefore, some markets/schemes turn out to be more attractive than others. Moreover, the intra- and inter-day (day ahead) fluctuations of prices in the electricity markets give rise to spreads. This is due to the different marginal costs of generation and demand and the market penetration of conversion technologies. Certain types of storage can take advantage of these price differentials.

Figure 2 shows the annual average day-ahead price and the average daily price spread in the day-ahead market in the market areas DK1 (Western Denmark) and DK2 (Eastern Denmark). The plot illustrates the average daily value of moving 1 MWh from the hour with the lowest day-ahead price to the hour of the highest price.

In the entire period the average price spread was close to 70% of the average price. Despite a significant expansion of wind power, this ratio has been constant.

Many aspects can contribute to these trends:

- Increased transmission capacity, e.g. to Norway
- More effective markets (utilization of transmission capacity, market framework, transparency)
- Improvement in flexibility and the dynamic properties of thermal power plants
- Increased capacity of electric boilers
- More flexible demand in general
- Increased market-based curtailment of wind power, i.e. When negative prices in day ahead and participation in balancing market

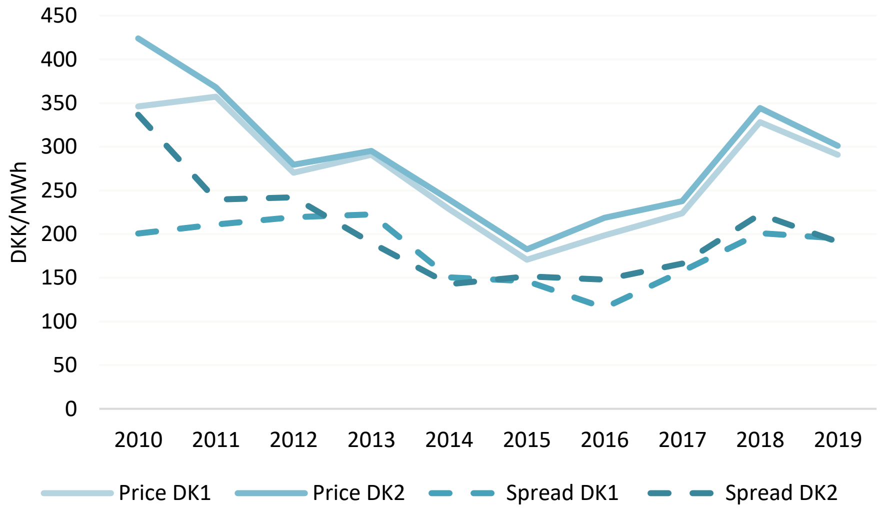


*Figure 2. Average day-ahead price and daily price spread in DK1 and DK2 (1.1.2010-3.12.2019).*

Other drivers affecting the system value of storage are listed in (Ea Energy Analyses, 2011)[7], here reported in Table 3. The table predicts a slight decrease in the system value in the three analysed countries. Some aspects contribute to value creation (more VRES penetration, phase-out of conventional generation), others (e.g. implementation of other flexibility measures) reduce the benefits related to storage deployment.

[7] This study performed by Ea Energy Analyses targeted EVs specifically; however, they can be considered as an electric storage option.

| Aspect | Influence on system value (from -5 to +5) | Germany | | UK | | Denmark | |
|---|---|---|---|---|---|---|---|
| | | Weight | Effect | Weight | Effect | Weight | Effect |
| More wind power | 5 | 90 | 4.5 | 100 | 5.0 | 75 | 3.8 |
| More solar power | 2 | 100 | 2.0 | 10 | 0.2 | 5 | 0.1 |
| More hydro | -5 | 10 | -0.5 | 10 | -0.5 | 0 | 0.0 |
| More pumped hydro | -4 | 100 | -4.0 | 50 | -2.0 | 0 | 0.0 |
| More natural gas | -2 | 25 | -0.5 | 25 | -0.5 | 25 | -0.5 |
| More biomass | -2 | 100 | -2.0 | 100 | -2.0 | 100 | -2.0 |
| Phasing out of nuclear power | 2 | 75 | 1.5 | 10 | 0.2 | 0 | 0.0 |
| Scrapping of thermal plants | 2 | 100 | 2.0 | 100 | 2.0 | 75 | 1.5 |
| Increased transmission capacity | -3 | 50 | -1.5 | 75 | -2.3 | 100 | -3.0 |
| Demand response development | -1 | 50 | -0.5 | 75 | -0.8 | 75 | -0.8 |
| New technologies for ancillary services | -2 | 10 | -0.2 | 10 | -0.2 | 10 | -0.2 |
| Dynamic tariffs | -1 | 50 | -0.5 | 50 | -0.5 | 50 | -0.5 |
| End-users access to hourly markets | -1 | 50 | -0.5 | 50 | -0.5 | 50 | -0.5 |
| Involvement of EVs in ancillary markets | -5 | 75 | -3.8 | 75 | -3.8 | 100 | -5.0 |
| **Total** | | | -0.3 | | -0.4 | | -0.5 |

*Table 3. Drivers for system value development. From an analysis of system value of electric vehicles made for Toyota Europe (Ea Energy Analyses, 2011).*

Technical development and diversity

Several storage technologies, led by Li-ion batteries, are experiencing a notable cost decline because of industrial advancements. Moreover, the wide spectrum of storage technologies and their versatility make them suitable for different applications.

Tariff design

Electricity tariffs are often flat. These are easy-to-conceive and implement, but may not reflect the real-time costs of power transmission and distribution. Tariffs could dynamically reflect losses and the capacity constraints, varying by location and changing every hour or even with shorter intervals. Dynamic tariffs would be more attractive than flat tariffs for storage technologies. However, dynamic tariffs are more complex, difficult to predict – also for providers of storage – and potentially expensive to implement. Consequently, dynamic tariffs may prove to bring more burdens than benefits to the energy system. Ultimately the objective of tariff design is to have cost-oriented tariffs. Hence, both feed-in and consumption tariffs should represent both the fixed and variable expenses associated with using the electricity grid.

Recently a number of Danish distribution companies have introduced time-of-use (TOU) tariffs with two steps for households and three steps for companies. These tariffs depend on the season (winter/summer), the time of day and the day type (weekend/weekday).

The presence of dynamic tariffs at transmission and distribution level (e.g. TOU or real-time tariffs) may create an additional incentive for storage technologies. This aspect depends also on the regulatory definition of storage

(Section 4.2), which is often ambiguous and heterogenous among different countries (Gissey, Dodds, & Radcliffe, 2018).

Energy and capacity markets

As thermal power generators are being squeezed out of power markets, the capacity balances are expected to become tighter. In energy only markets a tight capacity balance will impact the price volatility and possibly the price level, through which new capacity is promoted. As a last measure to increase the capacity, it is possible to establish a strategic reserve. A strategic reserve is Stringently regulated by EU regulation (Energinet, 2019).

Energy markets comprising both energy and capacity components have enabled the deployment of storage technologies. Several studies found that capacity payments are important for the financial viability of existing or soon-to-be-installed storage facilities (see for example (Borozan, Evans, Rodrigues, & Strbac, 2019) and (RSE, PoliMI, 2018)). The UK capacity market – which ensures security of supply - awarded 501 MW to battery storage technologies in December 2016 and some of the units will participate also in the national Enhanced Frequency Regulation market[8]. The system operator notifies storage units in case of need; these must be available all the time, or else a heavy penalty is charged. Time-limited contracts as opposed to open-end obligations may open up the possibility of participating in other markets (Gissey, Dodds, & Radcliffe, 2018).

In energy-only markets, capacity scarcity would be reflected in the power prices in the form of price spikes in hours with a tight capacity balance. Energinet is monitoring the need for a strategic reserve on a regular basis (Energinet, 2019).

Markets for different commodities

As for HT-TES, the unit can participate in both electricity and heat markets. This is especially true where district heating is widespread, such as in Denmark. Heat can be recovered from the discharging cycle and the storage facility can be equipped with a by-pass valve to create a broad operational range for heat production. Normal operation would maximise the electricity output (as electricity is normally more costly), but occasionally heat could be prioritised. This opportunity increases the unit flexibility and adds a revenue stream when convenient.

[8] The auction was of the T-4 type, meaning that it occurs 4 years before operations. Therefore, such units should enter into functioning in late 2020. Source: Luigi Michi - Terna (in Italian). Last accessed: March 2020.

## 4.2 Barriers and limitations for storage business models

Asset ownership

Asset ownership is a crucial issue to identify revenue streams for storage assets. In this context, the main point is whether utilities (DSOs and TSOs) are allowed to own and/or operate storage facilities (Insight-e, 2015).

In general, European TSOs are not allowed to own generation or storage facilities (European Parliament, 2009), even if exceptions have been made: Terna, the Italian TSO, has run storage projects from 2014 to investigate their aptness to provide network support[9]. However, Terna is not allowed to operate the units in the markets, such as the spot and the ancillary services markets. If a third party owns and operates the storage, the projects gains in financial viability.

Classification of storage assets

Storage units are defined as generators in most European countries, despite not providing positive net electricity flows. In several circumstances, storage assets need to pay both generation and consumption fees, thereby reducing the profit margin. In Denmark, a storage facility can by definition (Energinet, 2019):

- Absorb electrical energy from the grid and deliver it back at the point of connection, or instead use it internally in the installation
- Absorb electrical energy from renewables locally and inject it into the public grid at a later time, or instead re-use it internally in the installation

Parallel operation in several markets

The participation of storage assets in different markets may be a challenge. These challenges might be just as much a consequence of regulatory design as technical limitations. Since markets are designed to optimize system operation and for regulatory approval need to be technology neutral, these challenges might not be easily overcome. The case of the UK capacity market is an example that leads also to an underuse of the storage potential. Depending on the primary purpose, batteries can be unused for between 50 and 95% of their lifetime (Rocky Mountain Institute, 2015). Nonetheless, the optimal utilisation rate[10] depends on the market design (e.g. presence of availability/capacity payments), competitiveness towards other suppliers in the market and on the specific operational strategy. A low utilisation of batteries may be relevant since the continuous use of storage lowers its lifetime.

[9] For more information, see Terna (in Italian). Last accessed: December 2019.
[10] The *optimal* utilization rate is intended to be the one maximizing profits.

When arbitrage is the primary service provided, similar challenges occur. The optimised scheduling of a storage asset in the day-ahead (or intra-day) market leaves little room to deliver services in other markets. In (Ea Energianalyse, 2018) storage revenues are maximised for an average of two daily cycles; when entering ancillary service markets, the energy level might not be at the desired level to fulfil the market requests (e.g. too high SOC to provide down-regulation and vice versa). Such a unit might fail to meet its commitments and incur in imbalances costs and in extreme cases it may lead to market exclusion. The topic is further discussed in Section 6.4.

No monetization of system services

Besides the missed opportunities due to challenges related to cross-market compatibility, while grid investment deferral within a price area (see Section 5.1), voltage support and the quality of the power are system services which aren't monetized. In the Californian electricity markets, batteries are rewarded also for the accuracy of the ancillary services provision (pay-for-performance) and this aspect favoured the penetration of storage in the frequency response markets (40% of the overall regulating capacity in 2017, i.e. 280 MW). These storage assets are only flywheels and batteries used for fast response (State of charge, 2017), and the minimum size for the participation in such markets is 0.1 MW. The accuracy payment led to wide system benefits as well, for instance savings for ratepayers. Further details can be found in (Parvar, Nazaripouya, & Asadinejad, 2019) and (Xu & Silva-Monroy, 2016).

In the Nordic grid, high accuracy of the providers is motivated through imbalance prices and continues control. If a provider delivers ancillary services of poor quality, payment will lapse.

Self-cannibalisation

The market opportunities for storage technologies are influenced by their market penetration. In (Simioni, 2016), the projected revenues for thermal electricity storage in 2035 were shown to drop by over 70% when the storage size were to increase from 2 to 2000 MW.

(Ea Energy Analyses, 2011) found that if just 4-5% of future electric vehicles can deliver FCR (primary reserves), this would be enough to cover the entire need for reserves. However, the current attractiveness of such a market (more than 1,000 €/year per vehicle) is expected to be reduced to around 200 €/year per vehicle as the market and the technology develop.

Current implementation of more international ancillary services markets will increase the size and reduce the influence on the price from single investments.

# 5 Value matrix

The installation of storage assets goes to the benefit of different stakeholders. In broad terms, it is possible to distinguish between:

- The owner's revenue in current markets, i.e. the monetary compensation the storage owner receives for operating the asset in relevant markets
- The potential revenues that are not remunerated in existing markets
- Other system benefits that are not valued in current and future markets

In presence of perfect and undistorted market functioning, all monetary benefits should be entirely reflected into market prices. Markets are basically a tool to efficiently reach wanted objective. Day ahead market is established for efficient hour to hour dispatch, FCR market to secure availability of capacity to deliver fast frequency response according to product definition etc.

Transmission and distribution investment deferral should, for instance, represent those market hours where interconnection capacity is nearly saturated. In case of congestion, the unaccounted marginal monetary value coincides with the price differential between market areas.

Among other things, regulation can also cause imperfect market functioning. This can be related e.g. to TOU tariffs influencing the price structure, or to barriers hindering the participation in different markets. It is in this context relevant to consider that market and tariff designs reflect a broad selection of considerations, not just those of a specific technology. Hence addressing one design imperfection, may inadvertently result in another, possibly more severe, design imperfection.

Massachusetts case

In (State of charge, 2017), a report prepared by various stakeholders in Massachusetts, a breakdown of the system benefits is presented (Figure 4). The study finds that 1766 MW/2125 MWh of storage would be socio-economically optimal (given storage prices at that point in time). These would contribute to reduce system stress, defer T&D investments and lower the wholesale market prices in the State and in the neighbouring regions for estimated system cost savings of 2.3 billion USD over 10 years (or 130 USD/kW a year), which also go to the advantage of ratepayers. Revenues from the markets account for 1.1 billion USD, which may not be enough to cover the total project costs (estimated to settle between 0.97 and 1.35 billion USD). Overall, the unaccounted system benefits largely top the regulated revenues. These equal the increase in economic welfare due to the installation of the considered units and thus the monetary streams that do not go directly to the storage owner/manager.

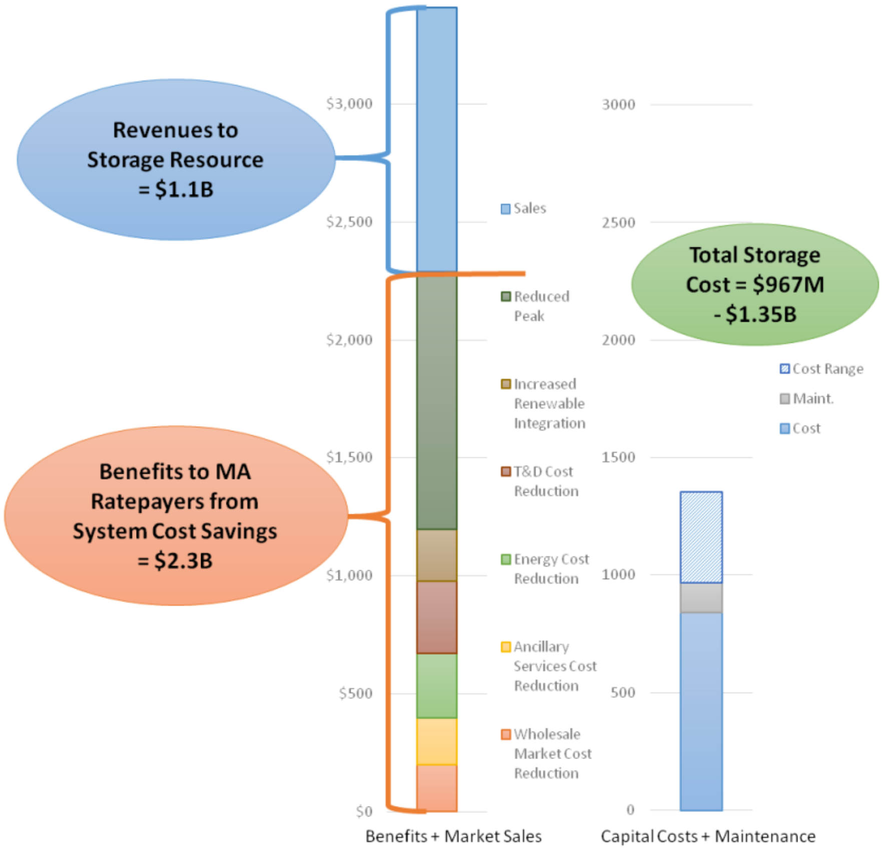


*Figure 4. Estimated monetary benefits of storage integration in Massachusetts. Source: (State of charge, 2017).*

In the Massachusetts case the system costs benefits are larger than the revenues to the storage operator. This is expected to be due to a less developed market system (e.g. with fixed tariffs for generation or demand) and the results cannot directly be transferred to the Danish setup.

## 5.1 System services and opportunities for storage

The focus of this section is on the services and system benefits energy storage can provide. Some of the services are delivered through energy markets in Denmark (they are referenced in each of the subsections); certain are remunerated in other countries, e.g. in the US, or are not linked to any compensation at all.

The value and opportunities related to the installation of energy storage can be articulated in the following areas:

- Arbitrage in the day-ahead and intra-day markets, which can reflect system needs such as:
    - Deferral of investments at transmission grid level to reduce congestion (between price areas)
    - Generation capacity deferral
- Balancing power, mFRR (manual reserves)
- FCR (Primary reserves) and aFRR (secondary reserves)

Other areas – discussed in the following - may include:

- Voltage support
- Black-start and grid-independent supply
- Hybridisation of VRES-based power plants

Besides the presence of a narrow market for black-start and grid-independent supply, the functions listed above are not yet remunerated in Denmark (and, in general, abroad), although hybridization can reduce grid connection costs. The lack of remuneration is because the need for these services are at present limited (Energinet, 2019).

Arbitrage

Arbitrage is an opportunity arising from the existence of price spreads in the electricity markets. Trading can take place in the day-ahead, intra-day and balancing markets. A storage facility can purchase energy during hours with low prices and sell it back to the network at high prices. Business models based on arbitrage can differ from one system to another.

The fundamental interest of a storage bidding into the day-ahead market is to identify the cheapest and most expensive hours. The price difference should be enough to outweigh the losses in the charging and discharging cycles. There are only a limited number of bid forms in the day-ahead market, none of these directly compatible with storage, hence optimising the operation of storage units requires skilled strategists. However, this is also the case for other technologies, like CHP, and bidders may compensate through appropriate bidding strategies. Based on historical prices, storage can bid for buying and selling in specific hours of the day. This could be done as *price independent hourly bids*. If prices turn out to be very different than expected, the strategy can be largely suboptimal.

Another approach could include the use of *price dependent hourly bids.* This strategy has the risk that the number of accepted bids for buying would not fit the number of accepted bids for selling.

However, many industrial end-users purchase electricity under a free-volume contract. They pay the day-ahead price for each hour plus a small mark-up. The mark-up covers the retailer's profit as well as possible imbalance costs. By operating a storage unit behind-the-meter under such conditions an owner can easily optimise the charging and discharging patterns of the battery. Prices are known and there is no risk of imbalance costs. The retailer would then need to learn how the storage was used to minimise his imbalance costs. This setup would also have the benefit that operation could include the incentive from a TOU tariff. To make the setup work the local demand would need to be sufficiently large to absorb the full capacity of the battery.

Regulating power

Demand and supply of power need real-time matching and storage units can serve this purpose. This entails up- or down-regulation based on the system needs at any moment in time. The volumes traded in the regulation markets are generally a modest fraction of day-ahead volumes, yet they can be a revenue source for storage technologies.

A common Nordic market (*Regulérkraftmarkedet*) exists to correct imbalances in real-time. Stakeholders willing to participate submit their bids to the TSO and the TSO orders regulating power bids as needed in real time. Regulating power must be fully activated within 15 minutes. Activation can start any time and the duration varies. The settlement is based on marginal pricing and on an hourly basis.

Frequency regulation

A stable grid frequency is essential for a safe operation of the system. The following reserve capacity markets are established in the synchronous area of continental Europe (which includes Western Denmark, DK1):

- Frequency Containment Reserves, FCR (primary reserves). They deliver a quick system-wide reaction when a power plant or a transmission line trip (49.8-50.2 Hz)
- Automatic Frequency Restoration Reserves, aFRR (secondary reserves), activated in the areas where the tripping took place. In the continental Europe synchronous system, the full activation of such units within 15 minutes from the notification signal are required in Denmark today, but will be reduced to 5 min in future European activation market for aFRR expected to be implemented in the Nordic earliest in 2023.
- Manual Frequency Restoration Reserves, mFRR (tertiary regulation). This market is related to the provision of regulating power. There exists the possibility of reserving the capacity in advance (remunerated

through an availability payment), or to enter the energy-only *Regulé-rkraftmarkedet (see above).*

Eastern Denmark (DK2) is part of a different synchronous region (the Nordic region) and frequency stability is regulated through different markets:

- Frequency Containment Reserves for Normal operations FCR-N (50.1 – 49.9 Hz). Currently, this market is symmetrical but a possible split into up- and down-regulation products is under discussion
- Frequency Containment Reserves for Disturbances FCR-D (49.9 – 49.5 Hz)
- Manual Frequency Restoration Reserves mFRR (tertiary regulation).

The frequency quality in the Nordic system is not living up to the goals and three new markets for frequency response are in the design stage and will complement the existing:

- a Fast Frequency Response (FFR) market is expected to be implemented by summer 2020 only for the Nordic synchronous area (Energinet, 2019). The market should compensate for the slow response of FCR-D units (hydropower) and batteries and flywheels are listed as suitable contributors to this need (ENTSO-E, 2019)
- a FCR (primary reserve) market complementary to the current FCR-D for frequencies between 50.1-50.5 Hz (down-regulation). The Nordic TSOs are continuingly addressing solutions to relevant system requirements (Energinet, Fingrid, Statnett & Svenska kraftnet, 2020), including any needed improvements of the FCR (primary reserve)
- a common Nordic aFRR market[11]; further details on the creation and modernization of the Nordic markets for both aFRR and mFRR can be found in (Nordic Balancing Model, 2019). Energinet identifies min 30MW the market demand for aFRR in 2022 (DK2) (Energinet, 2019).

Both Nordic and continental TSO's are in the initial phases of discussions to introduce a new control system relevant for energy storage. The system – called an Energy Management System, EMS – allows to deliver FCR with some extra flexibility. A key feature is that the supplier has the possibility to shift from the reference state of zero charging (before frequency response) to charging or discharging. This is relevant if a battery's SOC is too low or high to provide the agreed-upon service. For instance, when the SOC indicates that the unit can only deliver up-regulation for 15 minutes, then it can shift to a reference of

[11] The onset of such a market is unknown as of March 2020, but the proposal entails a pay-as-clear mechanism (Nordic Balancing Model).

charging. A unit can therefore deliver FCR by investing in some additional capacity (MW), but less volume (MWh). The system can be used both with symmetrical and asymmetrical delivery.

As an example, a 1.25 MW/1 MWh battery might opt to deliver 1 MW FCR up regulation. When the SOC is low (e.g. below 25%), a signal is sent to change its reference state, so that the battery can charge with 0.25 MW. In practice, even if the capacity is reserved for an entire hour, the required service duration is shorter, typically 15 minutes. The idea is that the battery should still be able to deliver 1 MW of up regulation, by being able to ramp up charging to 1.25 MW if the frequency drops down to the lower limit.

Allowing such flexible systems may encourage new technologies, like batteries and demand response, to participate in the reserve markets.

Voltage support

Voltage control is ensured by injecting or absorbing reactive power into/from the grid. Keeping the nominal voltage level in the grid is paramount to ensure grid stability and the optimal functioning of the equipment. Voltage control (*Spændingsregulering*) is generally managed centrally by the grid operator, which owns or activates suitable components (compensators, on-line large synchronous generators, capacitors etc.). Compensation should occur locally for various reasons (impossibility to transfer reactive power over long distances, increase in transmission losses due to bigger phase angles). In broad outline, the grid code requires each generator to be responsible for keeping the voltage at the desired level and to act following disturbances. The Danish TSO Energinet has identified the need of additional 380 MVAR for compensation purposes in 2020, of which 340 MVAR in Western Denmark (Energinet, 2019).

Further possibilities, e.g. the establishment of bilateral agreements with specific providers of a fixed-price remuneration scheme, are under consideration in Denmark. Static and dynamic devices can provide voltage regulation by adjusting the phase between voltage and current, and thus the reactive power. Other than by big generators, this function is traditionally fulfilled by shunt reactors and similar technologies at high-voltage level; their size is typically large, in the order of tens or hundreds of MVAR. In Denmark, these units are owned and activated directly by Energinet.

Voltage regulation can be delivered by power electronics installed in conjunction with electricity storage. Given the current relatively limited size of storage units, this application is rather restricted to medium-to-low level networks. Batteries could for instance be used in conjunction with distributed PV generation to limit voltage fluctuations.

| | |
|---|---|
| Generation capacity deferral | Storage units can defer or even eliminate the need for new generation capacity, especially in systems where electricity markets cannot deliver the expected level of security of supply. This can be through capacity mechanisms as strategic reserves regulated by European regulation. These investments often concern dispatchable units that might run on fossil fuels. |
| Congestion mitigation | Congestion on transmission lines between price areas leads to the formation of locational wholesale market prices (high price on the importing side). Storage can be charged or discharged when this occurs, e.g. by performing arbitrage in the day-ahead market.<br><br>Congestion can also occur within a price area. If the congestion is not structural (many hours), an area may be kept as one price area, but other ways to balance the system need to be found. These include for example re-dispatch, with up- and down-regulation being active on each side of the congestion – also called local flexibility. Energinet is currently conducting a pilot project on local flexibility (Energinet, 2019)<br><br>In Western Denmark (DK1), a separate market (*Specialregulering)* exists as to provide network support without affecting the balancing prices set in the Regional balancing market (*Regulérkraftmarkedet).* In principle, *Specialregulering* addresses all kinds of network matters, but in the past years more than 90% of the traded volumes was related to bottlenecks caused by excess wind production in Northern Germany (Energinet, 2018). Hence, this is mainly a down-regulation service. In this market, players are rewarded through a pay-as-bid mechanism. |
| Black start and grid-independent supply | After a shutdown, the TSO needs to reinstate the normal grid functioning. To do so, the generators in charge of the black start must be equipped with the necessary grid-independent units. Batteries can provide this and other services that require grid-independent supply. For instance, when the grid is not able to power a substation's equipment, batteries can supply the needed electricity. Possible applications concern the start-up of motors, any DC component, communication and control equipment. |

In Denmark, Energinet ensures the international obligation to have at least one top-down (i.e. through interconnectors) and one bottom-up (i.e. a unit) restoration system per market area. The market is regulated through bilateral agreements, which shall encompass the requirements in Table 4. The technical specifications are challenging for state-of-the-art storage, as a ±100 MVAR temporary reaction and a long-lasting supply are out of current design practices and possibilities. However, these issues can be partially addressed with the installation of storage banks.

| Type | Krav |
|---|---|
| Spænding: | Minimum tilsluttet 150 kV i DK1 og 132 kV i DK2[26] |
| Aktiv effekt: | Minimum 30MW samt kunne håndtere momentane spring på ±10 MW.<br>Skal kunne reguleres trinløst |
| Reaktiv effekt: | Kunne håndtere momentane spring på ±100 Mvar |
| Egenforsyning: | Til drift i minimum 24 timer |
| Forsyning/brændsel: | Til minimum to opstarter og kørsel på maksimum last i 12 timer |

*Table 4. Requirements for units willing to provide black start. Source: (Energinet, 2019).*

Energinet has also established a market for the security of supply in islands connected to the mainland through one unique cable. The market is regulated via bilateral agreements and units are expected to be operational only in case of a fault in the interconnector (Energinet, 2019).

Hybridisation of VRES-based power plants

The hybridisation of VRES-based power plants with electric storage help to improve wind and solar integration into the system, while offering arbitrage and other market opportunities. Batteries may be connected to the DC side of PV installations and thereby reduces the losses of an AC/DC conversion and grid connection costs may be reduced.

Summary of opportunities

Table 5 summarises the above-listed opportunities along with a qualitative description of typical technical requirements, the type of storage suited for the application and the synergy potential with other functions. High, moderate and low synergy potentials refer to the technical feasibility of multi-service provision: this feasibility is for instance related to the number of hours required to supply the service in object.

| Service / Opportunity | Technical requirements | Storage type | Synergy potential |
|---|---|---|---|
| Day-ahead and intra-day) | Good efficiency and low wearing due to cycling | Short- and long-term | High |
| Balancing (regulating power) | Good efficiency | Short- and long-term | High |
| Frequency regulation (primary and secondary reserves) | Fast response time and ramping, strong power component and relatively limited discharge time | Short-term | High |
| Voltage regulation | Presence of power electronics | Short-term | Moderate |
| Black start and grid-independent supply | Large-enough volumes to power other units | Long-term | High |
| **Service / Opportunity** | **Comments** | | |
| Congestion in grid (between price areas)/deferral of investments | This aspect is included in the day-ahead market | | |
| Congestion in grids (inside price areas)/deferral of investments | No market exists for this purpose today, except for *Specialregulering*, although Energinet has initiated a pilot project to test market designs for local flexibility (Energinet, 2019) | | |
| Generation capacity deferral | This aspect is included in the day-ahead market and in possible future market for strategic reserves in DK2[12] | | |

*Table 5. Overview of services that storage units can provide and related requirements.*

## 5.2 Opportunities for storage in a Danish perspective

Table 6 gives an overview of the existing and planned markets in Denmark for frequency regulation and other system services; the capacity need is also displayed and defines also the maximum possible penetration of any technology in the markets. The size of the FCR (primary reserve) and aFRR (secondary reserve) markets is relatively small if compared to the balancing and spot markets.

In the Appendix, Table 9 reports the main requirements as well as the remuneration schemes for units participating in the Danish ancillary services markets; additional obligations are listed further down. Often, a disparity exists between market design and requested unit performance.

According to the current rules, the supplier of FCR (primary reserves) must contract capacity for at least the duration of one time segment (one hour in

[12] For further details refer to (Energinet, 2019).

DK2, or four hours in DK1). Reducing the time segment to one hour or less would give more flexibility for operating the storage. The establishment of 15-minute imbalance settlement periods in the intra-day and balancing markets are being pursued at the Nordic and European levels[13].

It is worth noticing that the profitability of a storage unit is highly dependent on the market area (DK1 or DK2). In DK1 the unidirectional (up *or* down) participation of units in the FCR (primary reserve) market is possible, whereas the service must be symmetrical in DK2 (FCR-N, which handles the largest volumes, is symmetrical. FCR-D is only up regulation). The European Regulation 2019/943 explicitly states that upward and downward balancing[14] capacity should be procured separately. In addition, the existence of a 20 mHz deadband in DK1 may have positive effect on the operation of batteries (ignoring the impact on frequency that the deadband may have).

Value matrix in the Danish context

Out of all the opportunities discussed, three of them are directly linked to one or more existing and continuously operated markets in the Danish context. Storage units can receive a direct remuneration for exercising arbitrage in the spot markets, for providing frequency regulation and balancing services.

Frequency control is delivered through different markets wherein the penetration of storage is not equally possible. The minimum required bid of 5 MW in the mFRR market would typically require aggregation with other sources. On the other hand, storage units fit the FCR (primary reserve) requirements and short-term storage also the forthcoming FFR (in DK2).

Other services may be remunerated on a more discontinuous basis, such as support in case of congestion inside a price area (which is a potential future market, (Energinet, 2019)). However, congestion hours within Denmark occur very limitedly at present. In the future beyond 2025, a growing need for flexibility might require new investments and storage could find a relevant revenue stream in connection with transmission investment deferral. For the time being, this opportunity does not constitute a significant opportunity for value-stacking. Figure 5 shows the projected power exchange in 2025 through a 600 MW interconnector within Denmark. The flow exceeds the line capacity for a very limited number of hours a year.

[13] Nordic balancing model. Last retrieved: February 2020.
[14] The term *balancing* refers here to all kind of services meant to restore and stabilize grid frequency.

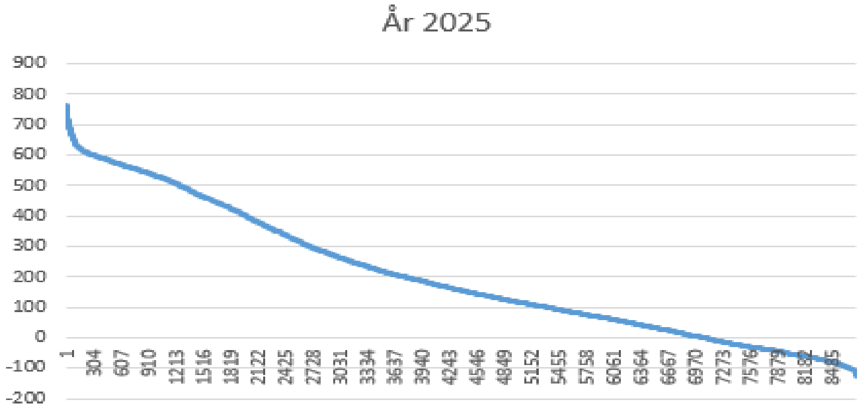


*Figure 5. Simulated power exchange through a 600 MW interconnector within Denmark (yearly duration curve). Courtesy of Energinet.*

The market for black start is hardly accessible to state-of-the-art storage units (Table 4), with high capacity (30 MW) and long duration of service (24 h). The island reserves do not offer remarkable opportunities for value-stacking (a unit needs to make its capacity available). Finally, the establishment of delivery of voltage control from providers is studied in a pilot project carried out in Lolland (Energinet, 2019)The opportunities differ between DK1 & DK2 because of the diverse regulatory framework and market characteristics. In particular:

- Rules can hinder or favour the participation in several markets. In principle, the Danish regulation does not prevent one unit to participate in more market mechanisms, yet (contracts which commits capacity) impediment to run the storage unit for other purposes may occur whenever a contract commits the capacity for a specific purpose. While balancing prices for FCR (primary reserves) and aFRR (secondary reserves) can include opportunity costs, the commitment of capacity ultimately does impede value stacking. Other design issues, i.e. the existence of a deadband, the size of the entry-level bid in the FCR (primary reserve) market or the symmetrical/asymmetrical nature of the products influence the business case of a storage unit (as discussed in Section 6.3)
- The market characteristics, which are also an effect of the underlying regulation, are paramount as they define the potential for any participant in the market. More specifically:
    - the degree of interconnection with the rest of the Nordics, which host large hydropower installations, can reduce the value of local balancing power (due to strong interconnection); on the contrary, a relatively lower capacity of interconnectors will increase the value of local balancing power because of reduced competition in the market (Energinet, 2019)
    - Traded volumes and clearing prices are key parameters.

For example, the volumes traded in the FCR-N market are larger than in the FCR-D; this is because the momentary frequency deviations from the setpoint *Δf* are more often in $|\Delta f| < 0.1$ Hz than elsewhere, but also because units need to respond to any deviation from 50 Hz without a permissible deadband (contrary to DK1).

| Ydelse | Behov | Bidrager til | Status |
|---|---|---|---|
| **Regulerkraft (mFRR-aktivering), herunder specialregulering** | Behovet for regulerkraft afhænger af balancen mellem elforbrug og elproduktion. | Frekvensstabilitet | Markedsgjort |
| **Manuelle reserver (mFRR-kapacitet)** | Behov på 684 MW i DK1 i 2020.<br>Behov på 623 MW i DK2 i 2020. | Frekvensstabilitet | Markedsgjort |
| **Automatiske reserver (aFRR-kapacitet)** | Behov på 90 MW i DK1 i 2020.<br>Behov på 20 MW i DK2 i 2020. | Frekvensstabilitet | Markedsgjort |
| **Frekvensstyrede reserver (FCR, FCR-D og FCR-N)** | Behov på 21 MW FCR i DK1 i 2020.<br>Behov på + 44 MW FCR-D i DK2 i 2020.<br>Behov på 18 MW FCR-N i DK2 i 2020. | Frekvensstabilitet | Markedsgjort |
| **Frekvensstyrede reserver (FFR)** | Behov er endnu ikke afklaret. Det er et nyt produkt, som forventes at komme i Q2/Q3 2020. Mængden udarbejdes internationalt for det nordiske synkronområde (DK2). | Frekvensstabilitet | Internationalt projekt igangsat |
| **Start fra dødt net** | Energinet har behov for to tekniske uafhængige dødstartsydelser i hver landsdel, som ikke er vekselstrømsforbindelser (AC) til udlandet. | Systemgenopbygning | Markedsgjort |
| **Reserveforsyning af danske øer** | Energinet har behov for reserveforsyninger på tre øer.<br>Bornholm: 94 MW<br>Læsø: 4 MW<br>Anholt: 1 MW | Systemgenopbygning | Markedsgjort |
| **Behov i forbindelse med revisioner, fx ekstra systembærende kapacitet** | Hvis bestemte komponenter er ude af drift på grund af fx revision, kan alle de øvrige beskrevne behov blive påvirket. Fx ekstra systembærende kapacitet, hvor behov opgøres løbende og indkøbes igennem udbud. | Spændingsstabilitet, vinkelstabilitet | Markedsgjort |
| **Spændingsregulering og reaktive effekt kompensering** | Behov for spændingsregulering i normaldrift medfører udarbejdelse af grundlag for fremskaffelse af spændingsregulering og reaktiv effekt kompensering med brug af teknologineutral tilgang for al produktion tilsluttet eltransmissionsnettet. Spændingsregulering under fejl er nødvendig for system stabilisering og spænding genopbygning. Det er obligatorisk krav for al produktion tilsluttet eltransmissionsnettet og er dækket i RfG'en. | Spændingsstabilitet | Pilotprojekt på Lolland og arbejdsgruppe for videre arbejde |
| **Nettilstrækkelighed** | Behov for at løse midlertidige flaskehalse i eltransmissionsnettet. Ned- og opregulering skal ske i de bestemte steder i eltransmissionsnettet.<br>Behovet for nedregulering på Sydsjælland estimeres til op mod 85 MW i 2022. | Undgå overbelastninger | Håndteres i dag via specialregulering. Pilotprojekt for lokal fleksibilitet med henblik på øget markedsgørelse |
| **Effekttilstrækkelighed** | Energinet kan ved mangel på effekt etablere et udbud for en mængde MW for en given periode. Der er med de nuværende forventninger ikke behov for ydelser til at sikre effekttilstrækkeligheden i 2020. | Frekvensstabilitet | Markedsgjort |

*Table 6. Existing and potential markets for frequency regulation and other system services in Denmark. Source: (Energinet, 2019).*

# 6 Quantification of the system benefits

## 6.1 Economic benefits of storage in the literature

The prospects for storage technologies largely depend on the market design, competition from alternative technologies and the opportunities offered by the regulation.

Analysis of batteries in the UK

(Borozan, Evans, Rodrigues, & Strbac, 2019) analyse value-stacking for battery storage systems in the UK and in a hypothetical, desired market context. Figure 6 shows the market potential and the mutual influence among the six identified relevant services. Arbitrage shows good synergies with the other services, while being penalised especially by VRES support and, more marginally, by frequency regulation (FR). Out of the six modelled functions FR is found to be the biggest opportunity for storage; however, at present the UK ancillary services markets are based on long-term contracts and therefore a large part of these revenues is not attainable. Overall, the study unveils a potential of over 5000 £/kW when all functions are performed and over the entire battery lifetime (assumed to be 20 years). The cost of capital is 7% and the corresponding annuity factor 10.6. This result is in the same order of magnitude as the revenue stream of the Hornsdale battery in Australia (Figure 7), further discussed in the following.

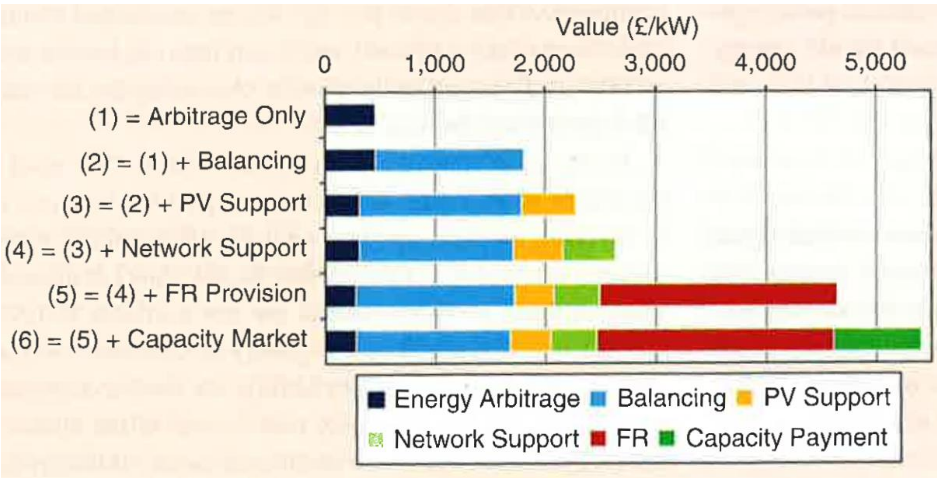


*Figure 6. Storage potential in different UK markets and their mutual influence when adding one service at a time. Revenues spanning over the entire lifetime are shown (Net present value). Source: (Borozan, Evans, Rodrigues, & Strbac, 2019).*

The potential for revenue-stacking also depends on the first selected service, in that the storage manoeuvrability in other markets is reduced by the need and convenience to comply with the first market rules. This fact is well highlighted in (Gundogdu, Gladwin, & Stone, 2019), where the stacked revenues for a 1 MW/1MWh battery in the UK frequency markets vary between 230-290 EUR/day, depending on the scenario (first selected service) and on the adopted strategy.

HT-TES revenues in electricity and heat markets

The combination of revenues from both the electricity and the heat markets could be of relevance for HT-TES, as stressed in (Simioni, 2016) and (Lo Brutto & Pérez, 2017). According to (Simioni, 2016), this storage type would be able to pay back the investment only from 2030 and to a large degree thanks to non-marginal revenue streams coming from the district heating market (roughly one third of the total). The financial viability of HT-TES projects is also linked to high spot prices and possible capacity remunerations.

It should be mentioned that the above analyses of HT-TES did not assess potential revenues in all relevant markets. HT-TES could in theory access other markets, especially the ones requiring continuity in the service provision (frequency regulation), and therefore stack additional value.

## 6.2 Pilot projects and their business cases outside Denmark

To test the technical and economic performance of storage in some of the previously listed areas, several demonstration projects are being carried out in Europe and in the world. The focus is on the provision of ancillary services as the fast and high-quality response of storage systems significantly improves grid management. In Lithuania, investigations have been conducted since mid-2019 to assess the role of batteries in the synchronisation of the Baltic region with continental Europe. In Hungary, the support of batteries to primary frequency regulation and to a local power plant delivering aFRR is also under study. A more detailed description can be found in (Central Europe Energy Partners, 2019).

A large battery storage system was installed in Southern Australia in 2017 and has participated in the electricity markets ever since. The storage capacity and energy component are 100 MW and 129 MWh respectively. Figure 7 reports the stacked revenues from the wholesale markets in September 2019. 55% of the revenues were obtained via the contingency FCAS (Frequency Control Ancillary Services) market due to a market reform (biggest volumes required and consequent surge in prices). Arbitrage plays a minor role, whereas frequency regulation stacked more than 1.3 million AUD (~ 800 thousand EUR). The unit guaranteed roughly 20 EUR/kW in revenues over September, that translates into a yearly estimated potential of over 250 EUR/kW. On a daily basis, this equals 650 EUR/MW/day, which is in the same order of magnitude as the previous findings.

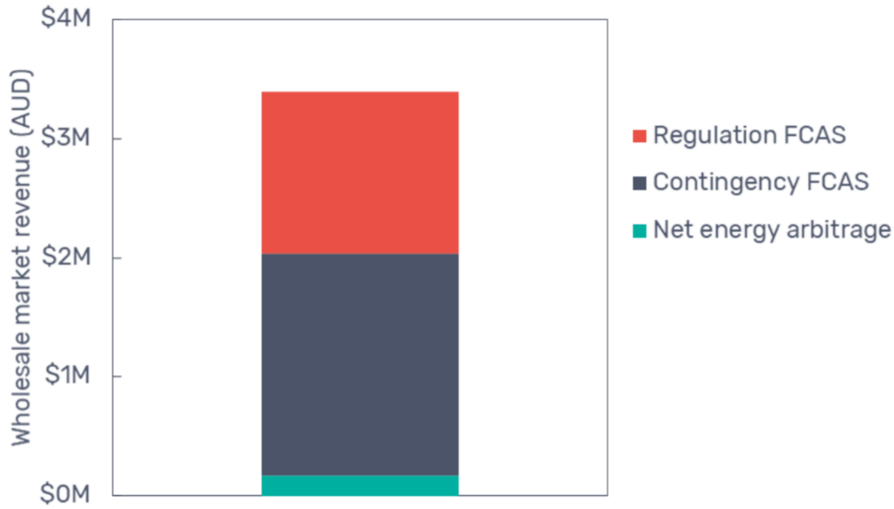


*Figure 7. Revenues for the Hornsdale battery in South Australia (September 2019). FCAS: Frequency Control Ancillary Services. Source: (Renew Economy, 2019).*

As for thermal energy storage, Siemens Gamesa has been testing its ETES concept in Hamburg since Summer 2019. No data on the system functioning is yet available, but the main project objective is to store energy for later use[15]. The facility has a volume of 129 MWh, but efforts will be made to scale up the size and reach beyond-1-GWh storage sizes.

## 6.3 Experiences from Denmark

As reported in Table 1, two significant storage demonstration projects were carried out in Denmark in the past years.

EnergyLab Nordhavn

The batteries installed in Nordhavn (Copenhagen) were tested mainly for the provision of primary regulation (TSO service) and peak shaving (DSO service). In (Radius Elnet, 2017), it is found that given the current regulation in DK2 it is not attractive for batteries to participate in the ancillary services market, even when combined with peak shaving functionalities. The Net Present Value (NPV) of all the tested combinations is negative and penalties largely contribute to the outcome; the FCR-N market offers the highest potential revenues, but by participating in the FCR-D market the unit incurs less penalties[16]. An improvement is observed under the hypothesis of DK1 FCR market conditions, that is unidirectional participation and 20 mHz deadband around 50 Hz with

[15] Source: Institute for Energy Economics and Financial Analysis. Last retrieved: March 2020.
[16] Penalties are paid when a provider does not deliver already agreed upon services.

no activation of the unit. The simulations entail a fixed configuration of the battery, which corresponds to the installation under test (2017): a capacity of 630 kW and an energy component of 460 kWh. The energy component (volume < 1 hour at rated power) is a critical parameter affecting the market performance.

Lem Kær

In the Lem Kær project, two battery units were installed in DK1 and their performance for the provision of ancillary services and load shifting was tested. The batteries had a volume of 15 minutes. The results highlight – among others - the impact of the auxiliary systems for heating and cooling on the storage profitability, considering the sizeable demand for power they require. In connection to this, grid tariffs also play an important role.

## 6.4 Value-stacking in 2025

The previous sections link the biggest opportunities for value-stacking to two main primary functions (or main supplied service):

- Energy-only market activities such as balancing power and arbitrage.
- Frequency reserves, which are provided through a set of markets targeting specific system needs. The literature review finds these applications to be the most remunerative.

In the Danish context, a plentiful array of strategies can be elaborated on these principles. Two main cases are considered here for illustrative purposes: participation in the day-ahead + the regulating power market; participation in the FCR (primary reserve) market + the day-ahead market.

Day-ahead market – daily price spreads

The average daily price spreads in the day-ahead market are reported in Figure 8 (year 2019). The trend is more uniform than in the FCR (primary reserve) market (described in Figure 10 and Figure 11), with price differentials being lower than summer values in the FCR/FCR-N/FCR-D markets, but comparable or even higher in winter.

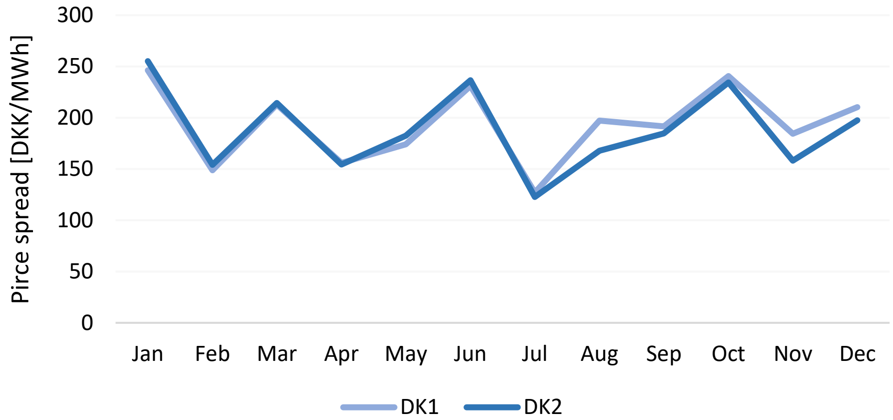


*Figure 8. Monthly average daily price spread in the day-ahead market. Year: 2019. Source: Nord pool.*

On the aFRR market

As clarified before (see also Table 9 in the Appendix), several markets for frequency reserves exist in Denmark. Demonstration and pilot projects in Denmark and abroad found primary reserve markets (in Denmark, FCR) to be the most attractive. The aFRR market in Denmark is less flexible than the FCR. Auctions are held on a monthly basis; the product is symmetric, and parties cannot withdraw from their commitments. These barriers are however related only to the market design, an issue already encountered in Germany[17]. Normally, FCR (or other primary reserve) markets offer more continuous revenue streams (Zeh, Muller, Naumann, & Hesse, 2016), but a remuneration scheme based on capacity bids makes aFRR (secondary reserve) markets equally attractive.

The aFRR market can in fact be considered a potential revenue source. In Denmark (DK1), the market size has been limited until 2020, as most of the capacity need was sourced through the Skagerrak link. This resulted in limited activation times for Danish units, mainly in connection to the unavailability of the Skagerrak cable (692 hours in 2018). In Figure 9 the aFRR activation signal is displayed for 2018 (DK1). The total aFRR was ± 100 MW in the same year but has been reduced to ± 90 MW from 2020 (Table 6). The energy exchanged in the market – integral of the areas in Figure 9 – was roughly 1400 MWh for up-regulation and 1200 MWh for down-regulation.

[17] Apricum group. Last retrieved: February 2020.

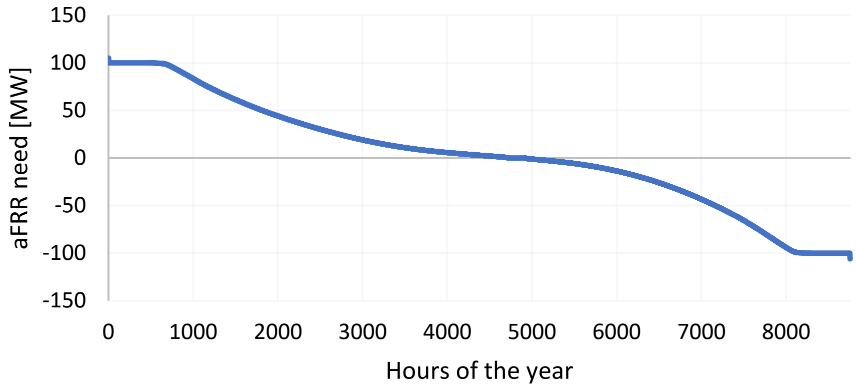


*Figure 9. Activation signal for aFRR units in DK1 (duration curve). Year: 2018. Source: Energinet.*

Starting from 2020, domestic units are required to provide the service. The capacity payment in the first months of 2020 ranged between 210 and 360 DKK/MW/h, determined under a pay-as-bid mechanism. These figures are in the same order of the availability payments found in the FCR market, as shown in the following. Due to the relatively new market conditions, it is difficult to draw general conclusions about the market attractiveness for storage. In broad terms, large storage units can fulfil the market requirements and benefit from a constant revenue stream.

FCR (Primary reserve) remuneration

Remuneration for the provision of FCR (primary reserve) markets is based on a capacity (availability payment) and on an energy component (Table 9 in the Appendix). Availability payments are on average higher in FCR-N than in FCR-D (Figure 10) and offer greater revenue possibilities in the case of up-regulation (Figure 11). In DK2 the participation in the FCR-N market is remunerated for the energy delivered and with the balancing price. Yet, this constitutes a modest income, as is the price differential between the day-ahead and the balancing markets (Figure 12). This is valid in average terms, though there exist a limited number of hours a year where the balancing price spikes. This situation can occur for instance if interconnectors are saturated and simultaneously a large domestic unit trips.

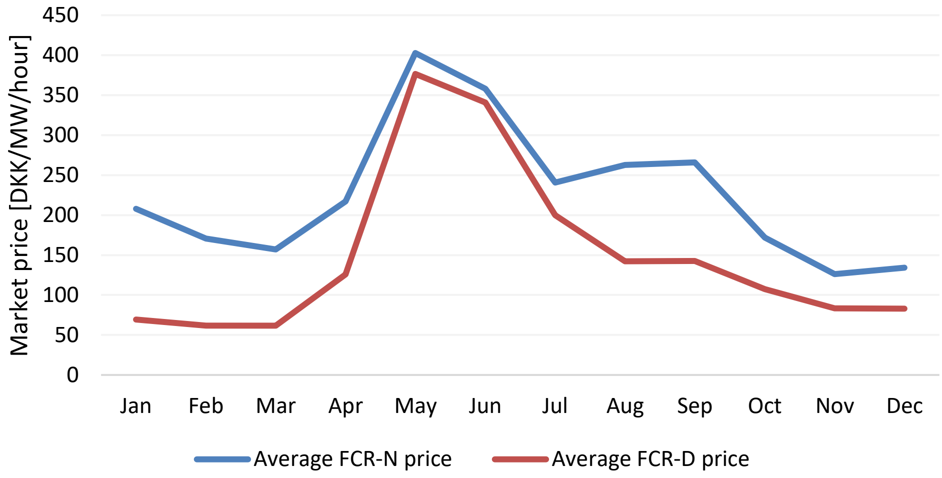


*Figure 10. Average monthly prices in the primary reserve markets (DK2). Year: 2019. Source: Energinet.*

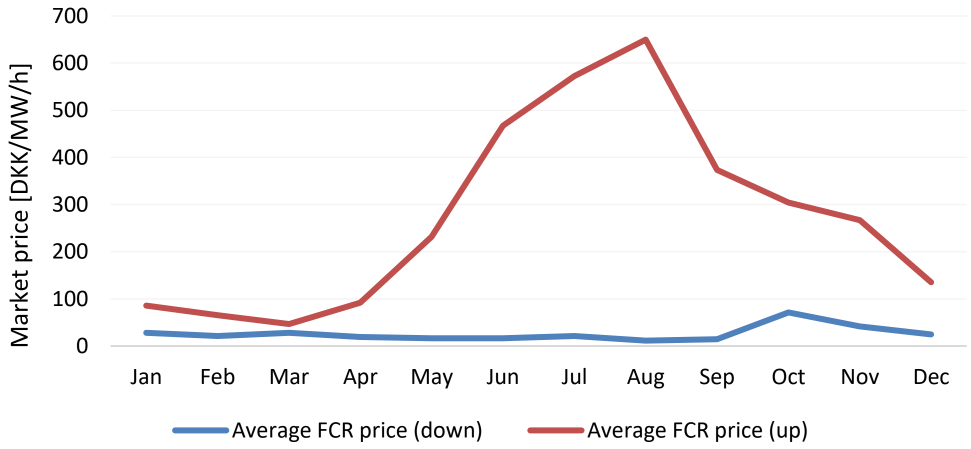


*Figure 11. Average monthly prices in the primary reserve market (DK1). Up and down stand for the unidirectional services. Year: 2019. Source: Energinet.*

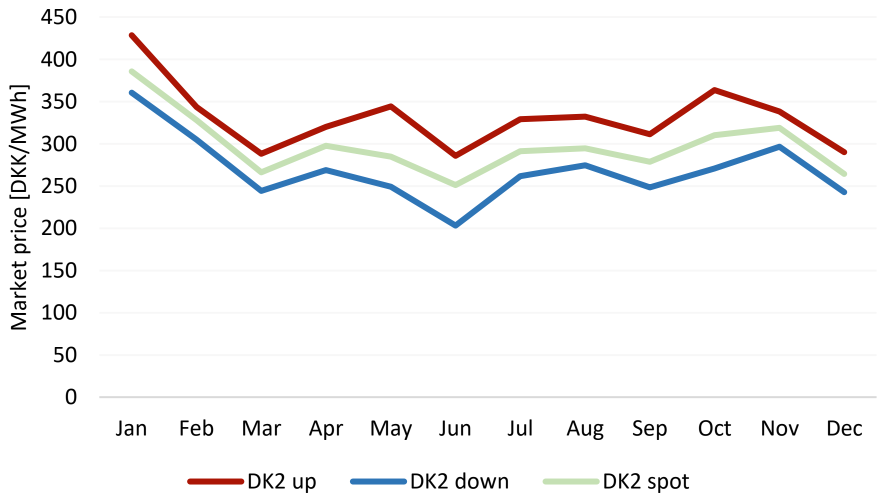


*Figure 12. Average monthly balancing and spot price in the Nord Pool area. Year: 2019. Source: Nord Pool.*

## Day-ahead and regulating power market

In this section we analyse the potential revenues of storage technologies in Denmark based on historic data and projected power prices for 2030 and 2050.

Bidding strategies

Day-ahead market strategies may differ on the type of bids submitted to Nord Pool. Several options are possible and include free-volume bids (Section 5.1), direct bids in hourly time slots and blocks of hours. Be it price-dependent or not, the direct bidding strategy is affected by risk (failure to deliver the contracted energy) and can lead to suboptimal revenues. In Figure 13 the optimized functioning in the day-ahead market is presented for a generic day of the year. The unit (volume-to-power ratio of 3.3) discharges in connection with demand peaks and typically performs two full cycles a day. Consequently, the energy content is highly fluctuating and often the SOC may be insufficient to provide e.g. balancing and frequency regulation.

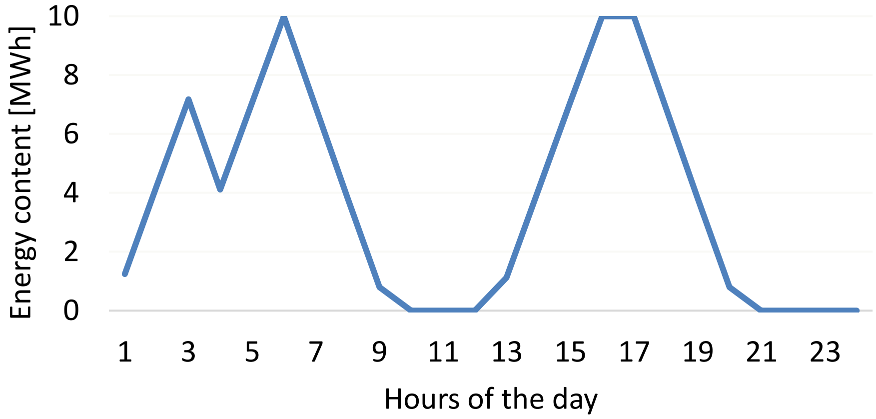


*Figure 13. Example of optimised daily battery functioning in the day-ahead market.*

On the other hand, by combining different markets (e.g. day-ahead and regulating power) the unit can adjust the energy content in order to minimize imbalances and the risk of penalties (Figure 14).

Storage can enter the regulating power market through a reservation agreement (remunerated with an availability payment) before the day-ahead market auctions close, or in an energy-only real-time market.

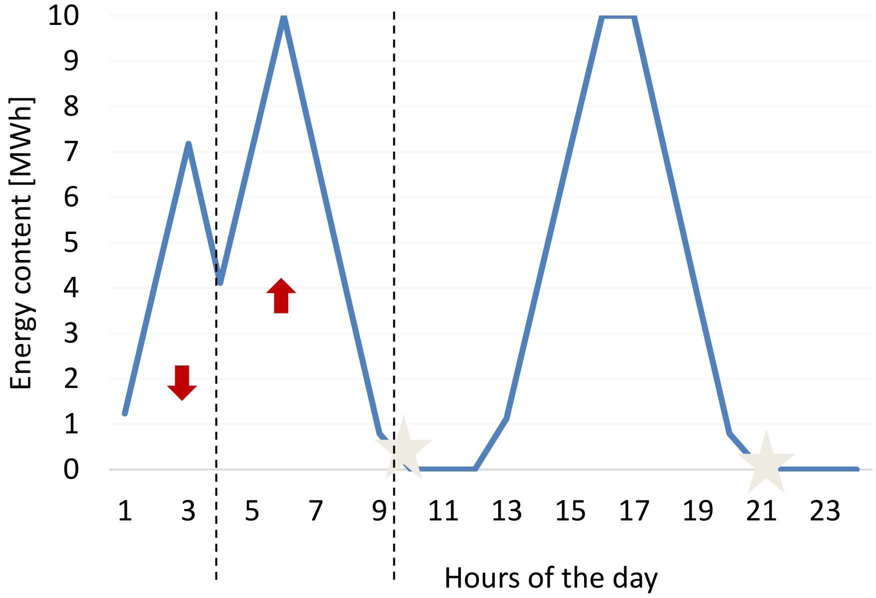


*Figure 14. Combination of different markets to adjust the energy content of storage. The unit can provide e.g. up-regulation first and down-regulation in the following to smooth the charging and discharging in the day-ahead market.*

Power market key assumptions

In (Ea Energianalyse, 2018), arbitrage revenues in the day-ahead market were calculated for both DK1 and DK2 and for selected years. The day-ahead prices are based on an European Balmorel model simulations with a number of assumptions: Fuel prices is from IEA's Sustainable Development Scenario (World Energy Outlook 2017), renewable energy expansion are taken from the countries reports to ENTSO-E, nuclear capacity is reduced in Germany and France, but increased in Finland, UK and Poland (total capacity is reduced from 110 GW in 2016 to 77 GW in 2030). Transmission expansion is according to TYNDP 2016 (ENTSO-E, December 2016).

Revenues in day-ahead market

The revenue for a 1MW/3.3 MWh battery is summarized in Table 7. In the study a simple two steps Time-of-Use (TOU) tariff was assumed for transport. The high tariff was active for four hours in the evening and was 2.5 times the low tariff (0.13/0.33 DKK/kWh). The values are obtained by optimizing the charging of the battery over a year. The revenue opportunity for future years is in the order of half a million DKK a year, with investment costs roughly nine times higher in 2030 and four/five times higher in 2050. As the next Section shows, a positive business case requires much higher yearly revenues. It should also be noticed that an optimisation strategy based on the day-ahead market such as the one reported (2 or more cycles a day) can cause a fast asset degradation.

| Year | Investment costs [MDKK] | Revenues - DK1 [thousand DKK] | Revenues - DK2 [thousand DKK] |
|---|---|---|---|
| 2016 | 12.44 | 324 | 318 |
| 2030 | 4.68 | 540 | 498 |
| 2050 | 2.29 | 508 | 478 |

*Table 7. Revenues from arbitrage activities in the day-ahead market (1MW/3.3 MWh battery). Source: (Ea Energianalyse, 2018).*

Optimisation with a flat tariff reduces the revenue significantly. The reduction corresponds to 40-44% of the revenue in 2030 (and even more in 2016). This illustrate the importance of the tariff design. The mechanical structure of a TOU tariff with a high ach day is positive for the battery revenue but may not accurately reflect the underlining costs. More advanced tariffs than TOU may be developed in the future.

The next case discusses a strategy when FCR (primary reserve) is the main provided service.

### FCR (primary reserve) and day-ahead market

The basic strategy considered in this section envisages the continuous access to the capacity payment offered in the FCR (primary reserve) markets. To characterize the opportunities for storage, the operations of a battery in the FCR (primary reserve) markets of Eastern (DK2) and Western Denmark (DK1) are presented in the following.

Case-study: battery providing FCR as the primary service

Depending on the market area, a battery needs to be charged for the energy deficit created in the market as a minimum. The energy deficit includes round-trip losses and all the energy not exchanged in the market but that contributes to the overall system balance[18]. It is assumed for simplicity that the battery is charged constantly in the day-ahead market with the average hourly energy deficit of the FCR market under study.

The total capacity requirement in the FCR-N market is 18 MW for DK2 (Table 6), hence the system bias is 180 MW/Hz[19]. Based on frequency data for

[18] The integral of the frequency fluctuations should be zero in principle, and so is the energy exchanged in the market. However, part of this energy is related to frequencies which lie *outside* the designed market ranges (e.g. 49.9 < f < 50.1 Hz in FCR-N). Overall, the integral within the market ranges might not be 0 and thus lead to an "energy deficit" within the market.

[19] This holds if up- and down-regulation are performed "in the same manner", that is with identical control characteristics.

December 2019, it is estimated that roughly 4500 MWh were required in the market in that month, or 3 MWh per hour on average for each unidirectional service (up and down regulation).

In order to assess the profitability of a unit in the market, a sizing problem is solved. A 1-MW battery willing to participate only in the FCR-N market in December needs to respond to frequency fluctuations by changing its State of Charge (SOC). The plot in Figure 15 illustrates the situation with a 5-second resolution frequency dataset. By assessing the deviation from the setpoint SOC, which is here assumed to be arbitrarily 0.5, it is possible to obtain the minimum battery volume for not incurring in any penalty (i.e., being able to deliver the expected response at any time). This value equals 7.5 hours. The average energy exchanged for this battery is 8.15 MWh (~ 1.1 cycles/day).

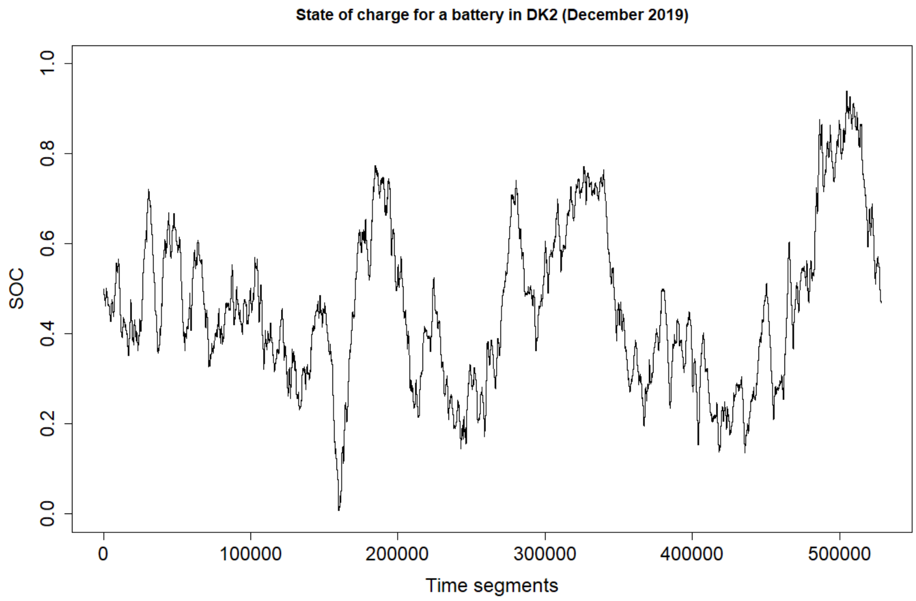


*Figure 15. Illustrative trend for the SOC of a battery in the FCR-N market (December 2019).*

If the DK2 FCR (primary reserve) market was designed as in DK1 (Appendix Table 9), the volumes traded therein would be only 53% of the energy exchanged in FCR-N. This is due to the presence of a 20 mHz symmetrical deadband. Assuming to provide only up-regulation, the unit volume results in 3.5 hours.

Accepting a contained penalty level can also be part of the strategy. By choosing to not deliver energy in a contracted period, the battery owner gives up the capacity payment, but can reduce the unit size. Storage is a capital-intensive asset and business cases can be refined to find an optimal unit size.

Estimated revenues

The impact of small penalty levels (5%, 10%) on the cash-flow of batteries is assessed in Table 8. Cost figures are derived from the Danish technology catalogue (DEA and Energinet, 2019); operation and maintenance costs are neglected as their effect is limited. The figures do not include costs and revenues from arbitrage activities (i.e. from the charging pattern in the proposed strategy). Estimates for the availability and energy payments are based on 2019 data.

| Case | Battery volume [h] | Availability payment [MDKK/year] | Energy payment [MDKK/year] | Investment cost in 2025 [MDKK] | NPV[20] (2025) [MDKK] |
|---|---|---|---|---|---|
| FCR-N up- and down-regulation | 7.5 | 2.0 | 0.14 | 12.1 | 0.71 |
| FCR up-regulation (no penalty) | 3.5 | 2.0 | 0.04 | 6.5 | 6.66 |
| FCR up-regulation (5% penalty level) | 3.2 | 1.9 | 0.04 | 6.0 | 7.11 |
| FCR up-regulation (10% penalty level) | 3.0 | 1.8 | 0.03 | 5.8 | 7.34 |

*Table 8. Influence of market design and penalty level on the cash-flow of a battery in 2025.*

Table 8 shows that in the three cases where battery provides only up regulation 3-year access to FCR (primary reserve) capacity payments covers the battery investment costs. Assuming to operate with a limited amount of daily cycles (~ 1.1 cycles/day as reported before), this case leaves room for further years of operations and therefore profits[21]. The net present value shows that all business cases based on primary frequency reserves are profitable. Even in the relatively worst case (7.5-hour battery) the Internal Rate of Return equals 8%. However, providing an asymmetric service has a positive impact on the battery business case. It should be noticed that a 10-year lifetime is a conservative estimation, as under the hypothesis of 1.1 cycles/day roughly 4000 cycles would be performed throughout the economic lifetime.

A comparison to the literature

The estimated revenues from the availability payments (~ 2.0 million DKK/year) translate into a daily potential of around 700 EUR/MW/day, a number on the high side with respect to the other literature finding (Sections 6.1 and 6.2). The constant access to the frequency markets capacity payments is however possible for storage units with relatively large energy volumes, greater or equal than 3 hours in all the analysed cases.

[20] The NPV is calculated with a 7% discount rate and for a 10-year lifetime.
[21] Table 2 showed that a Li-ion battery can last for a number of cycles in the order of $10^4$.

The introduction of the market for Fast Frequency Response (FFR) in the Nordic synchronous area can be a potential additional revenue source; synergies between markets and a finer resolution (15 minutes) might open new opportunities and allow for more diversified and optimized strategies.

Seasonality

Even though the cases are only representative of a single year, Figure 10, Figure 11 and Figure 12 suggest that also seasonality is a potential factor to take advantage of. As FCR (primary reserve) is remunerated entirely or partially for the capacity made available, it is impossible to perform multiple services at once (or else, the unit shall pay a penalty). Storage facilities can therefore diversify their market participation on a seasonal basis, that is take part in the frequency regulation markets when prices are (expected) to surge and e.g. exercise arbitrage in the energy-only markets at any other time (Figure 8).

In the Appendix, Figure 17 shows that also capacity payments for providing FCR (primary reserve) in 2018 followed some seasonality, with generally higher prices in the summer and lower in winter. The price variance across days is more marked in DK1, where the market is asymmetric.

Finally, it is important to mention that depending on the specific location of the storage the prospects for value-stacking may be higher due to the already existing *Specialregulering.* Moreover, opportunities for providing local services may increase with the establishment of new remuneration schemes, at both TSO and DSO level.

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# 7 Appendix

## The ancillary service markets

Table 9 carries the requirements and the remuneration for units participating in the Danish ancillary services markets.

| | | | | | |
|---|---|---|---|---|---|
| **DK1 (Western Denmark)** | | | | | |
| FCR | 0.3 | Hourly | 20 mHz < $\lvert\Delta f\rvert$ < 200 mHZ | Availability payment (marginal bid) + imbalance settlement | Daily auctions. Asymmetrical service. Offers to be submitted for 4-hour blocks. Same bid for hours within one block. |
| aFRR | 1 (max. 50) | Hourly | After FCR | Availability payment (pay-as-bid) + marginal settlement[22] | Monthly bilateral contracts. Symmetrical product. Energy and capacity market. |
| mFRR | 5 (max. 50) | Hourly | After aFRR | Availability payment (marginal bid) + marginal pricing (equal to the balancing price) | Daily auctions. Asymmetrical product. Energy and capacity market |
| **DK2 (Eastern Denmark)** | | | | | |
| FCR-N | 0.3 | Hourly | 0 mHz < $\lvert\Delta f\rvert$ < 100 mHz | Availability payment (pay-as-bid) + marginal pricing (equal balancing price) | Daily auctions. Symmetrical product. Offers can be submitted for single hours or block of 3 or 6 hours. Energy and capacity market. |
| FCR-D | 0.3 | Hourly | 49.5 Hz < f < 49.9 Hz | Availability payment (pay-as-bid) + imbalance settlement | Daily auctions. Asymmetrical service. Offers can be submitted for single hours or block of 3 or 6 hours. |
| mFRR | 5 (max. 50) | Hourly | After FCR | Availability payment (marginal bid) + marginal pricing (equal to the balancing price) | Daily auctions. Asymmetrical product. Energy and capacity market. |
| FFR | Yet to be determined | | f < 49.7 Hz<br>f < 49.6 Hz<br>f < 49.5 Hz[23] | Yet to be determined | - |

*Table 9. Main features and requirements for the participation in the Danish ancillary services markets.* Δf *refers to the nominal frequency* f *of 50 Hz. Source: (Energinet, 2019).*

The required technical performance for the participation in these markets is summarised in the following:

- Half of the contracted capacity shall be supplied within 15 seconds and the remaining half within 30 seconds in the FCR (primary reserve) market. The service must ensure the regulation for at least 15 minutes but, as a rule, until aFRR (secondary reserve) takes over;

[22] The energy delivered is compensated according to the following: with the DK1 day-ahead spot price + 100 DKK/MWh for upward regulation (- 100 DKK/MWh for downward regulation) if the balancing price is lower than this value (higher); with the balancing price otherwise.
[23] Three types of reserves are envisioned and are activated as the frequency drops below different levels.

- Half of the contracted capacity shall be supplied within 5 seconds and the remaining half within 30 seconds in the FCR-D market. The reserve must be active for at least 15 minutes but, as a rule, until the system balance is restored (Energinet, 2017);
- In the FCR-N market, the reserve must be active in no more than 150 seconds and ensure at least a linear supply in the specified range;
- The secondary and tertiary reserves (aFRR, mFRR) shall be active in full in no more than 15 minutes (5 minutes for aFRR in DK2) and until the system balance is restored;
- Players in the FFR market can offer support for either 5 or 30 seconds but their activation time must be under 0.7, 1.0, 1.3 seconds for system frequencies below 49.5, 49.6, 49.7 seconds respectively (ENTSO-E, 2019).

Additional system needs (inertia, reactive reserves, voltage control) are purchased at need and regulated by bilateral contracts.

## Battery sizing with 5% penalty level

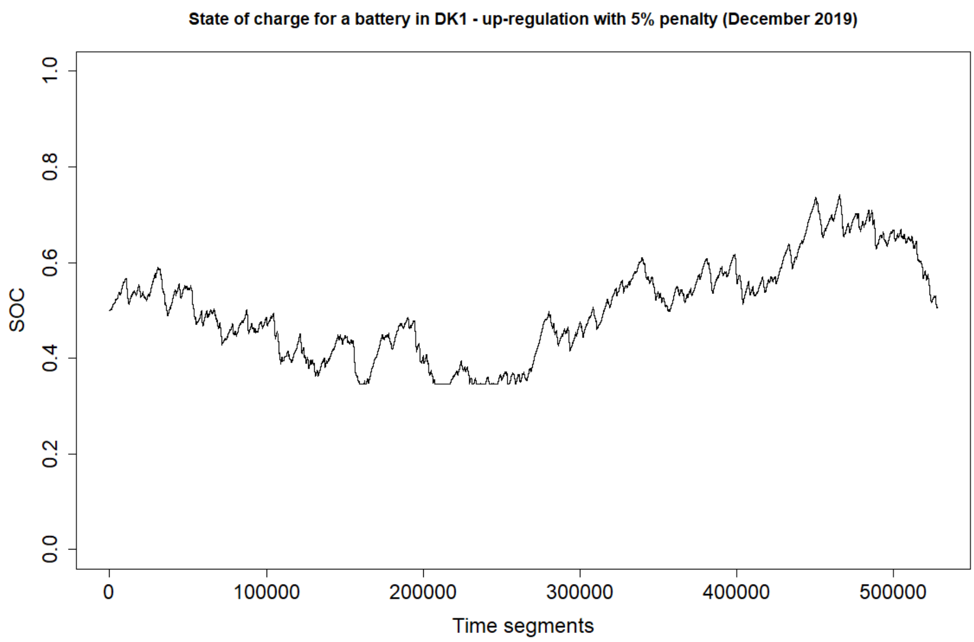


*Figure 16. Illustrative trend for the SOC of a battery in the FCR up-regulation market with a 5% penalty level (December 2019).*

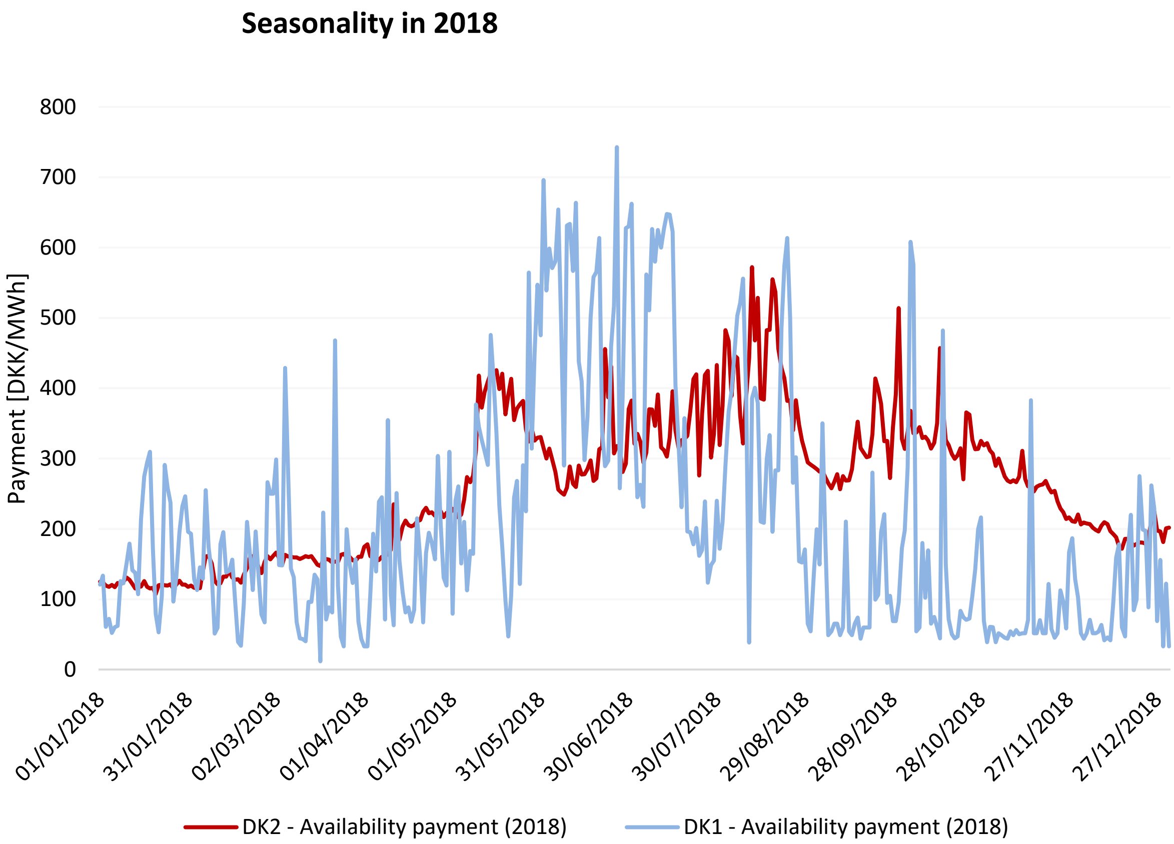


*Figure 17. Yearly trend for the availability payments in DK1 (FCR) and DK2 (FCR-N). Year: 2018. Source: Energinet.*