Feasibility study of large-scale battery implementation in the United Kingdom

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Energy Engineering and Management

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Abstract

The steep increase of renewable energy capacity has led to intermittence in the grid. Renewable technologies present a challenge of oversupply when wind and sun are available and shortage when these resources are low. Dependency on weather represents one of the biggest challenges of renewables not only because it generates grid instability but also creates high price volatility. The mass development of energy storage, such as batteries, could help overcome this challenge. This dissertation presents the analysis of how companies can monetize batteries to help stabilize the electricity grid and price of the country. The study is focused on the United Kingdom. This Master Thesis presents a study of the energy and electricity sector, an introduction of the power market, the state of the art of the battery market explaining current regulation and installed capacity and key players. The main research carried out is a price volatility analysis and a battery investment case to check if UK's volatility is large enough for batteries to be a revenue stream for price arbitrage. This thesis also includes an analysis of other current and future possible revenue streams for batteries in the country. The main outcome of this research is that batteries are a well suited technology to solve the price volatility problem and it is profitable to invest in them under certain conditions, but the capacity is limited and the implementation of them in the country is not sufficiently encouraged under current regulation.

Keywords: Energy Storage, Battery, Volatility, Price Arbitrage, Revenue Streams, United Kingdom.

Resumo

O aumento acentuado da capacidade de energia renovável levou à intermitência na rede. As tecnologias renováveis apresentam um desafio de excesso de oferta quando o vento e o sol estão disponíveis e escassez quando esses recursos são baixos. A dependência do clima representa um dos maiores desafios das energias renováveis não apenas porque gera instabilidade na rede, mas também gera alta volatilidade de preços. O desenvolvimento em massa de armazenamento de energia, como baterias, pode ajudar a superar esse desafio. Esta dissertação apresenta a análise de como as empresas podem rentabilizar as baterias para ajudar a estabilizar a rede elétrica e o preço de um país. O estudo é focado no Reino Unido. Esta Dissertação de Mestrado apresenta um estudo do setor de energia e eletricidade, uma introdução ao mercado de energia, o estado da arte do mercado de baterias explicando a regulamentação atual e a capacidade instalada e os principais players. A principal pesquisa realizada é uma análise de volatilidade de preços e um caso de investimento em baterias para verificar se a volatilidade do Reino Unido é grande o suficiente para que as baterias sejam um fluxo de receita para arbitragem de preços. Esta tese também inclui uma análise de outros possíveis fluxos de receita atuais e futuros para baterias no país. O principal resultado desta pesquisa é que as baterias são uma tecnologia adequada para resolver o problema da volatilidade e é lucrativo investir nelas sob certas condições, mas a capacidade é limitada e a implementação das mesmas no país não é suficientemente incentivada nas atuais regulamento.

Palavras-chave: Armazenamento de Energia, Bateria, Volatilidade, Arbitragem de Preços, Fluxos de Receita, Reino Unido.

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Chapter 1

Introduction

Before renewable energy's boom, grids transmitted power from non-renewable sources such as natural gas, oil and coal. This kind of energy suppliers have synchronous generators that help achieve grid stability by being able to step down or up the generation. For stability there has to be a balance between consumption and production and the grids need to be able to respond fast to disturbances in voltage and frequency. Spinning generators can react in 15 minutes slowing down or speeding up depending on the demand. In case of Europe, the system is kept at 50 Hz. Energy sources that are not constant, such as renewable, do not fare well with conventional grids. This challenge has exacerbated during these past years. Due to global decarbonization policies, the increase in electricity demand and the decrease of cost in renewable energy technology, the capacity of these technologies will increase by 50% between 2019 and 2024 according to IEA (IEA 2021). Currently, solar photovoltaic has close to 1 TW of installed capacity, wind 837 GW and hydropower 1330 GW (Jaganmohan 2021).

Renewable power sources create fluctuations in production due to the nature of intermittent weather conditions. This hard to predict generation leads to high price volatility. This issue is exacerbated when RE is introduced in small isolated electric systems such as the one of an island because they do not have the support from a bigger grid when any disruption happens making them more vulnerable against any fluctuation.

These issues should not be a barrier for the energy transition. System operators should study and implement new techniques and technologies to be able to adapt the grid to the new energy sources and maintain and operate the grid in the most effective way possible.

This Master thesis has the goal to tackle this exact problem. Energy storage, such as batteries, are known for price arbitrage. The owners of the batteries can purchase electricity when prices are low and sell it when prices increase protecting consumers from high price volatility. Price arbitrage can be a big revenue stream, but it is not the only one batteries can have. They are a great ancillary service. They help regulate the supply and demand fluctuations and congested transmission lines ensuring grid stability.

This research presents a feasibility study of implementation of batteries in the United Kingdom. It presents the analysis of how companies can monetize batteries to help stabilize the electricity grid and price of a country. It starts with a study of the energy and electricity sector and an introduction of the power market including market structure and main stakeholders analysis. The thesis continues with the state of the art of the battery market explaining current regulation, installed capacity and owners of the assets. It also includes an study of the strategy and future sustainable plans that the country has. Then moving on to the main research carried out. A price volatility analysis and a battery investment case are done to check if UK's volatility is large enough for batteries to use price arbitrage as a revenue stream. The dissertation also includes an analysis of other current and future possible revenue streams for batteries in the country such as Capacity Market and Ancillary Services. Finally, a SWOT analysis is done to weight the pros and cons of the technology and a success case of battery implementation in Australia is explained for further reference. The research is finished with conclusions and future work.

Chapter 2

Power Market

2.1 Introduction to UK

The United Kingdom (UK) is a country in north-western Europe and it includes the island of Great Britain, composed by England, Wales and Scotland, and the north-east part of the island of Ireland, sharing border with the Republic of Ireland. The UK is surrounded by the Atlantic Ocean and the capital city is London. United Kingdom has a total area of 242,500 km2. Figure 2.1.1 shows the location of UK in Europe.

Figure 2.1.1: *Map of Europe with UK highlighted*

Population of the country in 2021 was estimated to be around 67.65 million which comparing to Spain is +143% of Spain's population (BloombergNEF 2021).
Regarding economics, Gross Domestic Product, GDP in 2021 was estimated 3,108.42 billion USD (IEA 2021) and, according to the International Monetary Fund, GDP Growth is estimated 5.03% in 2022, 1,92% in 2023, 1.62% in 2024 (IMF 2021). The local currency of the country is the Pound Sterling GBP. Which the equivalent is 1 EUR equals to 0.83 GBP.

The current situation of the UK with Europe is that after 47 year of UK having been a part of EU, on 31st January 2020, Brexit was a political process that supposed the withdrawal of the UK from European Union.

2.2 Energy profile

UK is mostly an energy producer of oil and natural gas. Figure 2.2.1 shows the total energy supply by source in the country. Regarding coal, the share in generation fell to a record in 2021. Domestic coal production has fallen due to mine closures, floods and coal phase-out policy in force to end coal in power generation from October 2024 (gov.UK 2021). To compensate coal generators retirement, gas imports, mainly from Russia and USA, fill the gap in demand. As can be seen in Figure 2.2.1 coal supply has decreased over the years while other sources, specially natural gas, have increased and others, such as nuclear, have maintained their supply levels over the years.

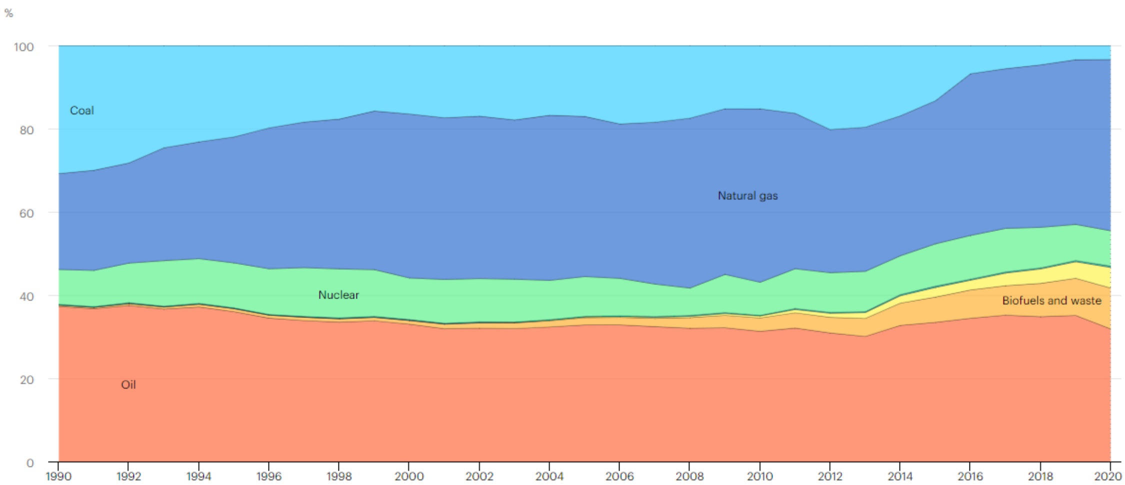

Figure 2.2.1: *Total energy supply by source, United Kingdom 1990-2020 (IEA 2021)*

Despite that the country produces oil and gas, an increase on demand over 2021, led the country to increase imports, especially of gas form Norway (gov.UK 2021).

Regarding final energy consumption by sources, transport (32%) and residential (29%) sectors lead the way representing together 61% of energy consumption. Followed by industry (18%) and commercial and public services (12%). The rest is represented by other smaller sectors (IEA 2021).

UK's final energy consumption is mostly on oil products and natural gas and to a lesser extend, electricity (IEA 2021). In Figure 2.2.2 it can be observed the final energy consumption share in percentage of the different energy sources UK uses.

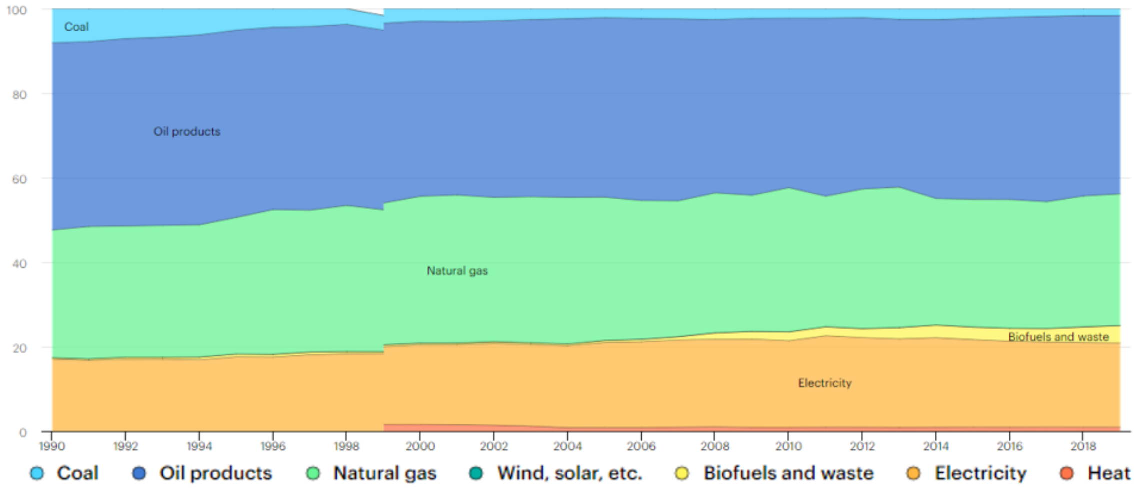

Figure 2.2.2: *Final energy consumption share (%) (IEA 2021)*

2.3 Electricity profile

2.3.1 Capacity and Generation

The installed capacity in 2020 was 100.73 GW of which 47.27 GW was from renewable sources. The capacity distribution can be observed in Figure 2.3.1: 33% natural gas, 24% wind, 13% solar, 9% nuclear, etc. (BloombergNEF 2021)

The total generation of the country in 2020 was 284.3 TWh. The electric power system of UK has very distributed generation mix that enables flexible operation. While fossil fuel generation is decreasing, still accounts for a 39% (mainly NG). Renewable generation is leading the mix with wind power in the top. Current

Renewable Energy Systems (RES) penetration is around 30-35%. In 2020, the shares were 37% natural gas, 24% wind, 16% nuclear, 14% biomass, 4% solar, 3% hydro, 2% other fossil fuels as can be seen in Figure 2.3.1 (BloombergNEF 2021).

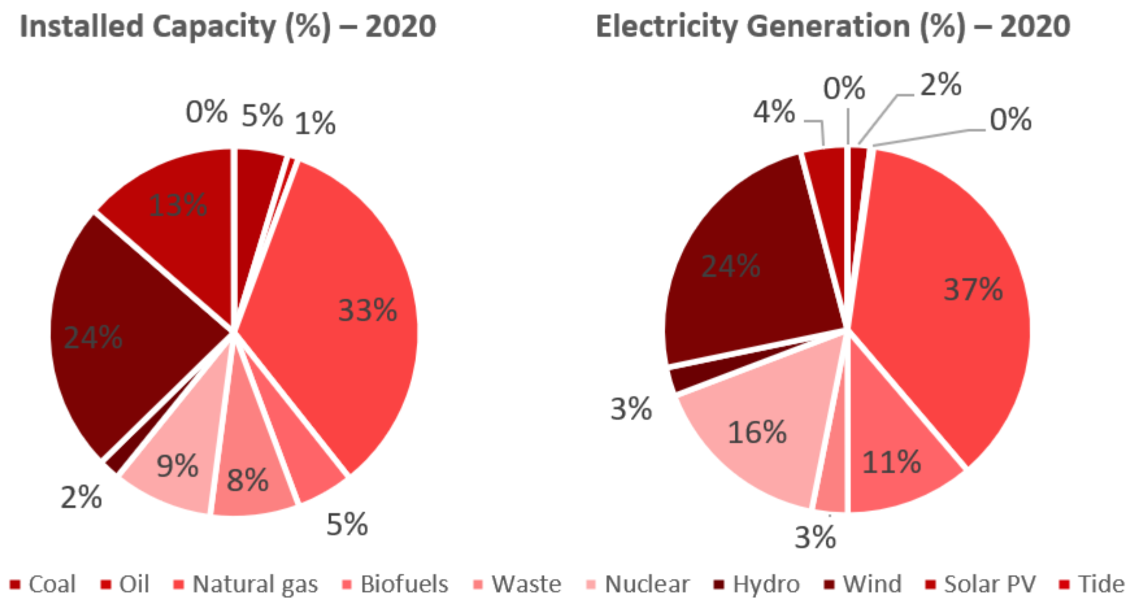

Figure 2.3.1: *Installed capacity and generation in UK in 2020 (BloombergNEF 2021).*

Regarding imports and exports, the country has been a net importer of electricity since 2010. In 2021 the total imports more than doubled while exports fell by 49%. The imports record levels are linked to increased capacity from the second UK-France inter-connector (further explained in section 2.3.3) and lower renewable generation due to weather conditions. In 2021, import/export balance was 21.2 TWh net import (National Grid 2022).

2.3.2 Consumption

Electricity consumption in UK is around 305 TWh/year. The use of electricity declined a 28% from 2005 to 2020, as can be seen in Figure 2.3.2, attributed to a decline in industrial activity and increase in energy efficiency. Peak demand is around 50 GW during winter months and summertime maximum load value is in the range of 65% of the peak load. Minimum load value is in the range of 34% of the peak load (Chestney 2021).

The consumption by sector is divided the following way: households, industry and commercial sectors have the largest share in electricity consumption and represent a 35%, 31% and 31% respectively (IEA 2021).

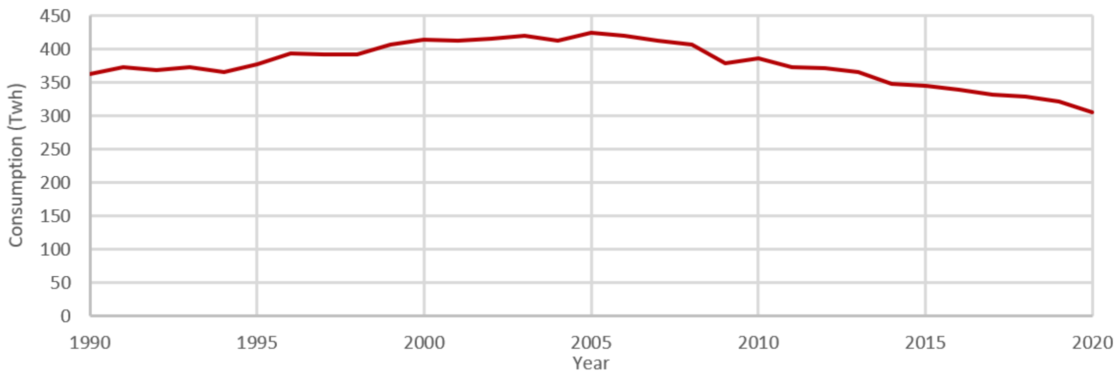

Figure 2.3.2: *Historical electricity consumption [TWh] (IEA 2021).*

2.3.3 Infrastructure and interconnections

Two types of electricity networks can be distinguished: the transmission and the distribution networks. In one hand, transmission networks transport electricity over long distances at high voltages, on the other hand, distribution networks carry electricity from the transmission system into the consumers at low voltages (UK 2022).

In England and Wales there are 7000km of transmission lines at 275kV and 400kV (National Grid 2022). Besides the transmission extension, as of 2021, National Grid operates 5 interconnectors with Europe:

- UK with France (IFA1): a 70km 2000MW HVDC between Sellindge (GB) and Les Mandarins (FR) (IFA 2022).
- UK with France (IFA2): a 240km 1000MW HVDC between Lee-on-the Solent (GB) and Troube (FR) (IFA 2022).
- UK with The Netherlands (BritNed): a 260km 1000MW HVDC between Kent (GB) and Maasvlakte (NL) (BritNed 2022).
- UK with Belgium (Nemo Link): a 140km 1000MW between Kent (GB) and Zeebrugge (BE) (nemolink 2022).
- UK with Norway (NSL): a 720km 1400MW between Blyth (GB) and Kvilldal

(NO) (NorthSeaLink 2022).

Besides the operating interconnections with mainland mentioned above, there are two more operating ones connected with the island of Ireland: Mayle and EWIC of 500MW each. There is also Vikin Link under construction, a 760km 1400MW between Bicker Fen (GB) and Revsing (DK) coming in 2023. And 5 more interconnectors under development as can be seen in orange in Figure 2.3.3 (National Grid 2022).

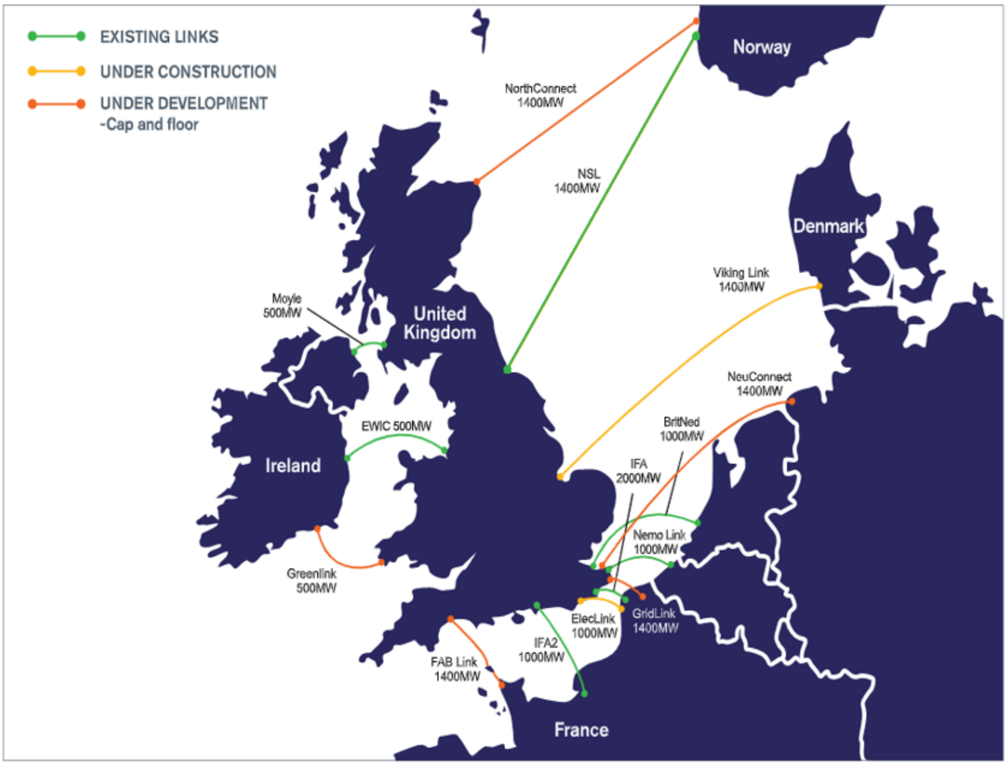

Figure 2.3.3: *Graphic representation of interconnection lines with UK (National Grid 2022)*

2.4 Power Market structure and players

2.4.1 Deregulation and Liberalization process

The Electricity Act in 1989 created major changes in UK's electricity sector deregulation. In case of a regulated market, energy can only be purchased from consumers' local supplier. It is a monopolistic marketplace, only one distribution company exists and the only price is highly regulated by the government.

Deregulation is referred as the reduction of government power in an industry, this allows to create a more competitive market free to prevail. Deregulation allowed customers to choose energy supplier. The competition between companies eventually led to more competitive prices. In case of the electricity market deregulation means that utility companies must divest all ownership and different utilities are responsible for distribution, operation, transmission and billing the customer (RedClay 2017).

Before 1989, the Central Electricity Generation Board (CEGB) was the owner of all the transmission system and controlled the generation and distribution of electricity in England and Wales. The remaining of the market was divided between the South of Scotland Electricity Board (SSEB) and the North of Scotland Hydro-Electricity Board (NSHEB).

After deregulation occurred, CEGB was split into 4 companies, three generators: PowerGen, National Power and Nuclear Electric and National Grid Company (NGC), responsible the transmission. On the other hand, SSEB split into Scottish Power (nonnuclear) and Scottish Nuclear. NSHEB became private and changed the name to Scottish Hydro. Also a regulatory agency, called the market regulator, was established named Office of Gas and Electricity Markets (OFGEM), which was governed by the Gas and Electricity Markets Authority (GEMA), to promote competition (RedClay 2017).
Figure 2.4.1 shows the current power market distribution with the responsibility of each key player.

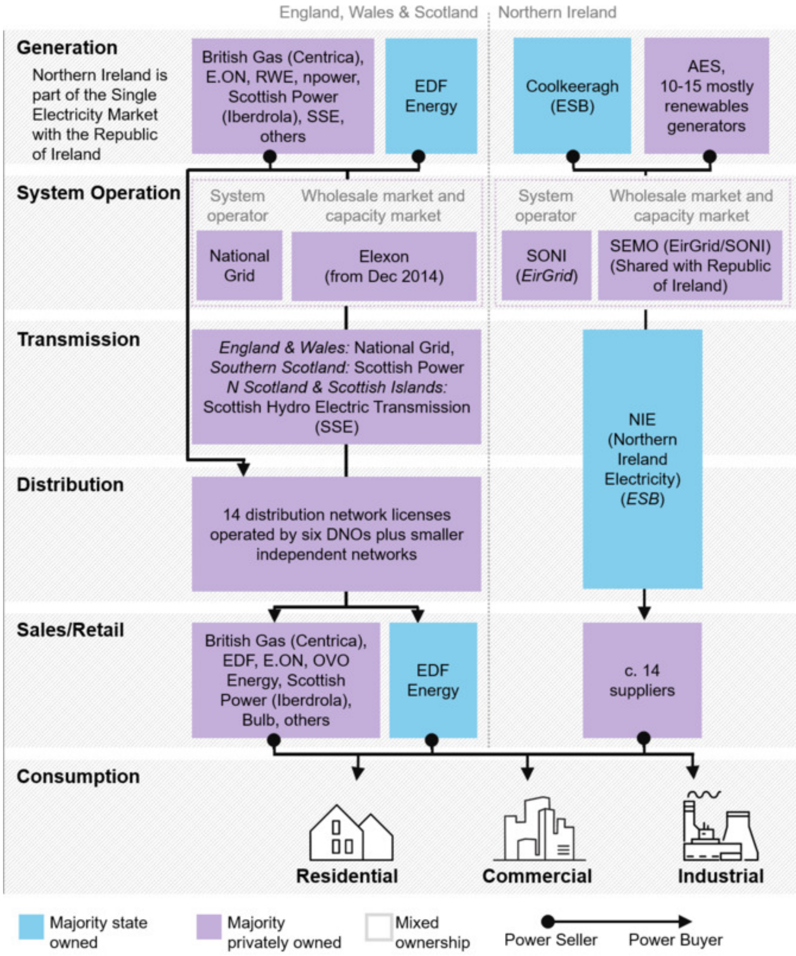

Figure 2.4.1: *UK Power Market structure and players (BloombergNEF 2021).*

2.4.2 Market structure and main stakeholders

Electricity market has become very diverse with over 38 power producers operating and a fast growing number of small power generators, as can be seen in Figure 2.4.2. The market diversification has allowed a transition from primary coal-powered country to a country with different sources of energy, with high penetration of renewable.

- **Generation:** over 38 power producers, of which small producers account for 38% of the generation.
- **System Operation:** National Grid Company regulates the supply that exists on the national transmission network.
- **Transmission:** Scottish Power Transmission Limited for southern Scotland,

Scottish Hydro Electric Transmission for the north of Scotland and the Scottish islands groups, and the NGC.

- **Distribution:** 14 licensed distribution network operators are in Britain; each one is assigned a regional area to service.
- **Retail:** competitive since there are lot of companies on this area. They buy electricity from the wholesale market or from generators and set the final price for electricity.

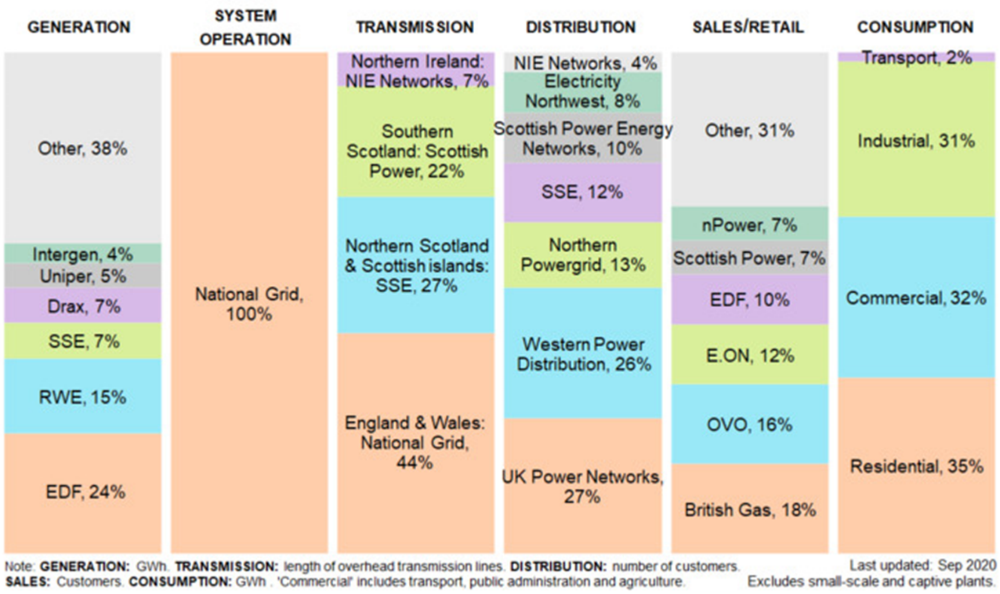

Figure 2.4.2: *Distribution of contribution of the different stakeholders of the UK's market (BloombergNEF 2021).*

2.5 Wholesale Market

One way of selling electricity in the UK is through the wholesale market. Customers buy energy from suppliers who have previously bought the energy in the wholesale market. The liberalization process explained in section 2.4 has made suppliers work in a competitive market, this way customers can choose which supplier they want to buy electricity from. Currently, there are two markets operating in GB (England, Wales and Scotland), NORD POOL and EPEX. Both markets operate in many countries in Europe and have similar DAM prices. NORD POOL trades higher volume every year.
Northern Ireland trades in the Irish market called SEMO.

2.5.1 NORD POOL

Nord Pool is the power market leader in Europe. It offers day-ahead and intraday markets to more than sixteen countries as can be seen in Figure 2.5.1. The market areas are: UK, France, Luxembourg, The Netherlands, Belgium, Germany, Poland, Austria and the Nordic and Baltic regions (NordPool 2022).

Figure 2.5.1: *Countries where Nord Pool operates (NordPool 2022).*

The total volume traded in the Nord Pool market in 2021 was 963 TWh, of which more than 15% was traded in GB, that is 147.3 TWh (NordPool 2022). There are two types markets:

- **Day-Ahead Market**. In this market, once a day a blind auction takes place. All orders submitted go into the aggregated curve of Offers and Bids and the point of intersection between them establishes the price and energy volume for the according time period. There is a 60 min and a 30 min day-ahead auction. The prices range goes between -500 GBP/MWh and 3000 GBP/MWh (NordPool 2022).

- **Intraday Market**. This market is open 24/7 all days of the year. It offers 15, 30 and 60 minutes changes. All orders and volume received are aggregated to calculate a market equilibrium. The intersection establishes the price and energy volume for that delivery period (NordPool 2022).

2.5.2 EPEX

Epexspot is part of EEX group. This market is the leading exchange for power spot market in Europe. The market areas are: Austria, Belgium, France, Germany, Great Britain, Luxembourg, The Netherlands, Switzerland, Denmark, Finland, Norway, Sweden and Poland as can be seen in Figure 2.5.2.

Figure 2.5.2: *Countries where epexspot operates (EPEX 2022).*

The total volume traded in the epexspot market in 2021 was 621.5 TWh, of which more than 10% was traded in GB, that is 63.4 TWh (EPEX 2022).

- **Day-Ahead Market**. In this market, once a day a blind auction takes place. In this case, participants have to send two orders: firstly the volume willing to buy or sell for each delivery period for all prices in the ranges of -500 GBP/MWh and 3000 GBP/MWh. Secondly, block orders linking the delivery periods together. With that, the supply and demand curve is established for each hour of the following day and determines the binding trades (EPEX 2022).

- **Intraday Market Continous**. This market trades continously, 24 hours with delivery on the same day. Electricity is traded every 5, 15, 30 or 60 minutes. The trade is executed as soon as buy- and sell- orders match between the prices of -9999 €/MWh and 9999 €/MWh (EPEX 2022).

- **Intraday Market Auctions**. In this market, a blind auction takes place two times per day, everyday of the year. Price ticks between -150€/MWh and 1500 €/MWh (EPEX 2022).

2.5.3 Historical prices

Taking as reference the prices in the EPEX market, Figure 2.5.3 shows the evolution of the baseload prices in the UK. In red is shown the annual average, in blue the monthly average and in grey the daily average in GBP/MWh. Over the years the prices' trend was pretty constant, but in 2020 prices decrease around 18% in annual average reaching an average price of 35,3 GBP/MWh. In 2021-2022, prices spike for the first time in 10 years with an increase of over 401% from 2020 reaching an annual average of 176,9 GBP/MWh in 2022. This price increase is due to lock downs, market instability and more recently, because of the abrupt increase in gas price led by Russia's invasion of Ukraine.

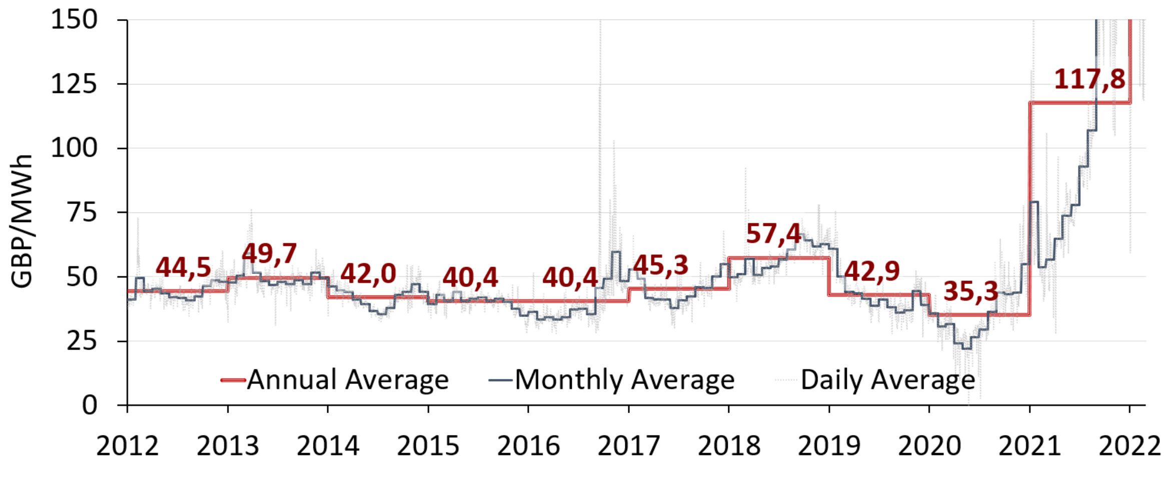

Figure 2.5.3: *EPEX Baseload Prices in UK from 2012 to 2022*

2.6 Low-carbon strategy and future plans

The UK has the target to achieve net-zero greenhouse gas emissions by 2050. The Nationally Determined Contribution (NDC) has set the goal to reduce economy-wide greenhouse gas emissions 68% by 2030 and 78% by 2035, relative to 1990 levels (Government 2021).

Renewable energy plays an important role in accomplishing these targets. Driven by declining renewables' costs, by 2050, UK expect more than 86% of their electricity to be generated by wind and solar (BloombergNEF 2021). Some of the main targets related to energy sources are the following:

- **40 GW of offshore wind capacity installed by 2030**, including 1 GW of innovative floating offshore wind.
- **5 GW of low- or zero-carbon hydrogen production by 2030**, linked to a goal to be able to capture 10 million mt/year of CO2 and store it under the North Sea.
- **By 2030, end the sales of petrol and diesel vans and cars**, which means that all vehicles will be required to have a certain zero emissions capability (e.g. plug-in and hybrids). In 2035 all vehicles should be 100% zero emissions.
- **Both onshore wind and solar are re-admitted to the next CFD auction** (explained in section 3.1.1).
- (BloombergNEF 2021) expects installed **energy storage capacity to rise from 1.3 GW in 2020 to more than 6 GW in 2025.**
- Establish **four Carbon Capture Units** in industrial clusters by 2030, **capturing up to 10 Mt of CO2 each year.**
- Regarding Nuclear plants, the country generates about 15-20% of its electricity from nuclear. In 2025 almost half of current capacity is to be retired, delivering new and advanced nuclear power. Only one plant, Hinkley Point C (3.200 MWe) is under construction. Government announced that they will provide round £385 million in an Advanced Nuclear Fund for the next generation of nuclear technology aiming, by the early 2030s, to build an Advanced Small

Modular Reactor (AMR). UK aims to **build a commercially viable fusion power plant by 2040** (Association 2017).

- The share of coal in generation fell from 39% in 2012 to just 2% in 2020. **There is a coal phase-out policy in force**, with a deadline to end coal in power generation from October 2024.

2.6.1 The Ten Point Plan for a Green Industrial Revolution

In 2020, the UK government announced that will be funding and supporting the following areas to hasten the green energy revolution (HM 2020):

Table 2.6.1: Ten point plans for a green industrial revolution summary (HM 2020).

Green Industrial Revolution		
Point	**Technology**	**Description**
1	Offshore Wind	Targeting to quadruple UK's offshore wind capacity up to 40 GW.
2	Hydrogen	World-leading electrolyzer companies producing 5 GW of green hydrogen
3	Nuclear Power	Investment in Advanced Nuclear and Small Modular Reactors
4	Emissions Vehicles	End petrol and diesel cars and invest in low emission vehicles
5	Green transport	Investment in rail and zero-emission bus services
6	Aviation & ships	Sustainable aviation fuels and R&D in zero-emission aircraft and ships
7	Buildings	Make buildings more energy efficiency, remove fossil fuels boilers
8	Carbon capture	Target to capture 10Mt of Carbon dioxide a year
9	Environment	Safeguard landscapes, restore habits and combat biodiversity loss
10	Innovation	Raise total R&D investment to 2.4% of GDP by 2027

2.7 Balancing services

NationalgridESP is the entity in charge of the balancing services in Britain's transmission system. It provides services to balance demand and supply to ensure electricity supply quality (National Grid 2022). Some of the core services are described here:

2.7.1 Frequency response services

Frequency Control Ancillary Services, known as FCAS, are services used to keep a constant electrical frequency on the system. In Great Britain, the frequency of the grid has to be controlled at 50 Hz plus or minus 1% (National Grid 2022).

Figure 2.7.1: *Summary of how FCAS react.*

The frequency of the system is controlled real time second-by-second by the balance between the demand and total generation of the system. There are two categories of frequency response:

- **Dynamic frequency response:** this response provides service continuously and it is used to manage the normal changes of the system second by second.
- **Non-Dynamic response:** this response provides discrete service only at a specific defined frequency deviation.

Figure 2.7.2 shows a summary of the services of frequency response.

Dynamic Containment (DC) It activates when the frequency moves 0.2 Hz from the 50Hz. It operates post-fault in order to meet the need for faster-acting frequency response.	**Dynamic Moderation (DM)** Manage sudden large imbalances and deliver fast response to keep frequency with limits of operation.	**Dynamic Regulation (DR)** Corrects continuous and small deviations of frequency and act pre-fault.
Mandatory response services In charge of keeping the frequency within operational limits. It automatically changes the active power output.	**Firm frequency response (FFR)** Route to market. Provides stability against price uncertainty under the mandatory service arrangements.	**Phase 2 Auction Trial** Procuring Low Frequency Static and Dynamic Low High frequency products through the EPEX SPOT Auction Platform every week.

Figure 2.7.2: *Types of frequency response (National Grid 2022)*

2.7.2 Reserve services

Because of changes on the demand or generation, at certain hours of the day, extra sources of power are needed to reduce/increase generation or consumption. The power sources that are available for these special cases are called reserve services and they allow national grid to manage the unexpected changes in demand that were not well forecast (National Grid 2022).
These services have different reaction velocity, here is a short list of the different reserve services ordered by shorter to longer timescale:

- **Fast Reserve.** It delivers active power rapid and reliable. It does so by reducing consumption from sources or increasing output from generation. It is the fastest reserve service.

- **Short-term Operating Reserve.** Acts similar to fast reserve with slower timescale. It is a source of extra power that meet reserve requirements.

- **Demand Turn Up.** This service allows any technology that is flexible to increase demand or reduce generation at certain times where demand of the country is low. This service is mostly used during the night.

- **Super SEL.** It decreases the sum of the minimum MW levels of the system by lowering the generating level to keep generators synchronized.

- **BM start up.** Service for any Balancing Mechanism that can not act in the timescales of 89 min. This service gives the system access to additional generation.

- **Replacement Reserve.** Service across European TSOs to decrease or increase active power.

2.7.3 System security services

These services are responsible for the security and quality of electricity across the whole transmission system (National Grid 2022).

- **Intertrips.** Automatic control that reduces or disconnects generation if there is a system fault event.

- **System operator to system operator (SO to SO).** Adjusts interconnector flows close to real time providing services with other transmission systems in Europe.
- **Restoration Services.** Contingency service used in case of a total or partial shutdown in order to restore power in the national electricity transmission system.
- **Transmission constraint management.** Used when some areas are congested an the system is unable to provide power to the location where demand is higher.
- **Maximum Generation.** This service allows the generation to use capacity outside the normal range of operation for some emergency situations.

2.7.4 Reactive power services

These services make sure the levels of voltage are kept within a range by absorbing or generating reactive power (National Grid 2022).

- **Obligatory reactive power service.** Service required by all generators to produce or absorb reactive power. This helps control voltage close to the connection point.
- **Enhanced reactive power service.** This service are for generators who are able to provide reactive power outside a specific range.

Chapter 3

Batteries' State of the Art

3.1 Regulation

The main entities in the electricity sector with a role related to energy storage and regulation are the following:

Office of Gas and Electricity Markets commonly known as OFGEM is the energy regulator of Great Britain. It is in charge of determining energy strategies, set policies and decide on regulatory issues. This entity works constantly with government to protect energy consumers (OFGEM 2022).
The system operator, National Grid, is in charge of the ancillary services which are the key for batteries as revenue streams.
Distribution Network Operators were in the lead on storage research because of past Ofgem funding programs such a Low Carbon Network Fund (currently inactive). One of the pioneering projects of grid-scale battery storage was from a DNO called UK Power Networks that commissioned a 6MW/10MWh lithium-ion battery storage in 2014 thanks to the Ofgem Low Carbon fund previously mentioned. Current programs boost utilities and private developers to lead gird-scale battery projects (Hassan 2018).

Energy storage was not defined separately in the legislative framework in the UK. In 2020, Ofgem confirmed that electricity storage would be treated as other forms of generation. But that still means that there is no specific energy storage regulatory regime. Although Ofgem and the Department of Business, Energy Industrial

Strategy are supportive of energy storage and agree that this technology provides benefits to the grid, there are no battery specific subsidies or any commitment from Government. This creates difficulty when developing a profitable business case because the project has to collect revenue from the multiple streams that will be mentioned (ancillary services, price arbitrage, capacity market, etc) (Hassan 2018).

In 2018, National Grid ran the first a tender dedicated to a new ancillary service. The tender was technology agnostic but developers were trying to use the over 1 GW capacity proposed to develop stand alone battery projects. This technology was popular because of ability to provide service within a second of a registered frequency deviation. The successful bidders won a four years contract.

In 2020, new laws were implemented in the UK. They allowed electricity storage projects of more than 50 MW to apply for ordinary permissions which reduce cost and time delays that were created by the previous regime called Nationally Significant Infrastructure Projects (NSIP) where they had to apply for tedious Development Consent Orders (DCO). This new legislation does no longer require DCO for sand-alone projects. There is no capacity limit for any project, before there was a limit of 50 MW and it was an impediment for investments and made larger projects divide into 49 MW to avoid a DCO. Finally new legislation has allowed to add storage facilities to existing generation sites (Ashurst 2020).

3.1.1 Active regulatory programmes

These are some of the active regulatory programmes that ofgem is leading where batteries can participate:

- **Dynamic Containment** ancillary services received, in the first round in 2020, six tenders from which two battery storage systems were accepted to boost the grid's resilience. These two systems will provide 90 MW of services. Tenders for this service will run every day of the week to help with frequency control (Lempriere 2020). More information about DC is explained in Section 4.2.3.

- **Dynamic Regulation Auction**. DR is a pre-fault frequency service that corrects continuous but small deviations in frequency. The auction went live on the EPEX auction platform on April 2022. It had a high price of 17

GBP/MWh and it drew attention boosting revenue for battery energy storage assets. After the first auction, 139 MW of battery capacity responded when a interconnector failed. (Lempriere 2022).

- **Contracts for Difference (CFD)** Government uses Contracts for Difference (CFD) as one of the main mechanism for supporting low-carbon electricity. To reduce the exposure to electricity prices, generators sell energy into the market as usual but CfDs provide a variable top-up from the market price to an agreed price. When market prices are high, these payments reverse, and the generator pays back the difference between the market price and the agreed strike price, which protects consumers from over payment.
  This type of contracts protect consumers from paying increased support costs when electricity prices are high and encourage investment in renewable energy by providing projects' developers with high upfront costs and long lifetimes and at the same time it protects them from volatile wholesale prices.
  Renewable generators in the UK that meet the eligibility requirements can apply for a CfD. To date, there have been 4 auctions which have seen a range of different renewable technologies competing directly against each other for a contract. Auction winners enter a private law contract with a government-owned company, the Low Carbon Contracts Company (LCCC). For the electricity developers that produce over a 15-year period, they are paid a flat (indexed) rate. This rate is the difference between a price for electricity reflecting the cost of investing in a particular technology ('strike price') and the average market price for electricity in the GB market ('reference price') (NationalgridESO 2022).

3.1.2 Co-located projects

One of the most popular ways of storage projects is co-location with generation, mainly renewable. One of the first projects in the UK, was a DNO that signed a contract with a private renewable energy company to build a 1.5 MW solar farm co-located with a storage system. This project was supported by Ofgem in its first Network Innovation Allowance program (Hassan 2018).

In the end of 2021, UK government implemented new storage policies. Eligibility for large-scale renewable including co-located energy storage to participate in the national Contracts for Difference (explained in Section 3.1.1) scheme. There was round four of this CfD auction on 13th December 2021. The change was that previously, CfD prohibited importing energy from the grid to co-located storage. Because the first co-located projects showed the benefits of it, specially in the increasing number of negative price periods, CfD now allow storage on renewable energy projects as long as the owner can demonstrate the ability to meter the battery properly (Liam Stoker 2021).

3.1.3 Stand alone projects

Lithium-ion technology is the focus for grid-scale stand alone battery storage systems. Although it looks promising, this model presents some challenges. There is revenue uncertainty, the contract terms are short (around 4 years) so projects have uncertainty in terms of revenue over the whole life time of the project. It has higher operational costs since the battery is charged as and end-user despite the same energy being put back to the system to be truly consumed by an end user (Hassan 2018).

3.2 Battery Market

UK currently has 1.3 GW of operational grid-scale battery storage units and by the end of 2022 a total of 1.81 GW is expected to be installed (SolarMedia 2021).
The planned capacity by regions can be seen in Figure 3.2.1. Most capacity, around 80%, is being built in the south region. Currently, South East region has the largest operational capacity and it is expected that keeps leading with the planned capacity for the next years. The reason behind this is the demographic distribution of the country since 27% of population lives in that region (SolarMedia 2021).

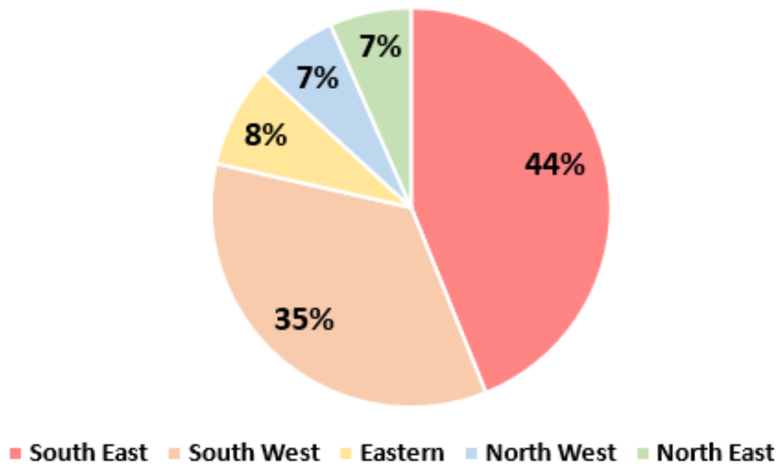

Figure 3.2.1: *UK's energy storage planned capacity be region (SolarMedia 2021).*

3.2.1 Battery owners

Table 3.2.1 shows the battery owners of the total current and future operational capacity. Gresham House, an assets management company, is the largest battery owner in Great Britain. They have a total portfolio of 425 MW after adding new assets such as 35 MW Port of Tyne battery, 25 MW Tynemouth battery, 30 MW Byers Brae battery, 10 MW Nevendon battery and expanded Glassenbury battery by 10 MW (Aurora 2022).

Every year larger scale batteries are being installed, over the last year, 100 MW CNIC, 50 MW Pivot Power battery and 49 MW Statera battery came online.
As an example, Zenobe's is adding 100 MW battery before the end of the year which main functionality will be to absorb reactive power.

Table 3.2.1: Key players on current battery market (Aurora 2022).

	Operational end 2021	**Operational by 2022**	**Units**
Gresham House	425	425	MW
Statera	149	149	MW
CNIC	100	150	MW
Gore Street	95	95	MW
Zenobe	69	169	MW
Sembcorp	60	120	MW
Centrica	53	53	MW
Pivot Power	50	50	MW
Others	49	289	MW
EDF	49	49	MW
FRV / Harmony	42	42	MW
Conrad Energy	40	40	MW
SUSI Partners	30	30	MW
Somerset Council	30	30	MW
Vattenfall	22	22	MW
Orsted	20	20	MW
TRIG	20	20	MW
E.On	10	10	MW
Downing	0	50	MW
Shell	0	5	MW
TOTAL	1313	1818	MW

Many asset owners have partnerships with companies that define their route-to market strategy. This strategy determines which distribution channels are the best ones to deliver a product and which are the target customers while providing optimization and risk management services. This route-to-market providers own software and have the experience to monetize assets across ancillary, balancing and wholesale markets. Some big portfolio owners, such as Gresham House are contracting different providers. Table 3.2.2 shows examples of operational projects with route-to-market partnerships.

Table 3.2.2: Route-to-market partnerships with operational projects (Aurora 2022).

Route-to-market provider	**Example Project**	**Asset Owner**
Arenko	41MW/41MWh Bloxwich battery	Gresham House
Habitat	15MW/22MWh Lockleaze battery	Gresham House
Flexitricity	50MW/75MWh Thurcroft battery	Gresham House
EDF	50MW/75MWh Whickham battery	Gresham House
Limejump	20MW/20MWh Lascar Works battery	Gore Street
Open Energi	10MW/12MWh Hill Farm battery	Zenobe
Tesla	7MW/15MWh Holes Bay battery	FRV/Harmony Energy
Statkraft	27MW/30MWh Boscar Grange Farm battery	Warrington Borough Council
Kiwi Power	30MW Fideoak Mills battery	South Somerset Council
Centrica	10MW Leverton Farm battery	Susi Partners
Origami	9MW Port of Tilbury battery	Gore Street

3.2.2 Planned Capacity

In 2030, UK expects to reach 5 GW of total battery capacity in line with increasing capacity of renewable technologies and in 2050 a total of 12 GW. The evolution of the different technology capacity can be seen in Figure 3.2.2. In pink is the planned battery capacity (Aurora 2022).

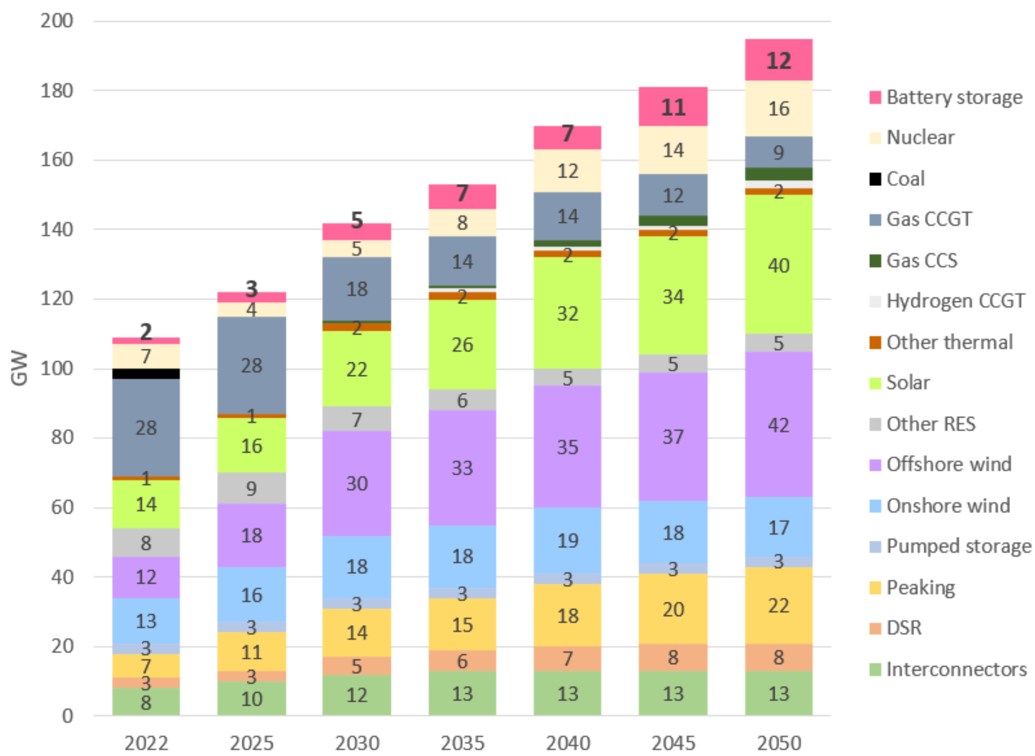

Figure 3.2.2: *UK installed capacity forecast from 2022 to 2050 (Aurora 2022)*

3.3 Revenue streams for batteries

In order to build a profitable and successful project, an analysis of the different revenue streams is needed. Of all services explained in section 2.7, batteries are eligible for some of them. This section will explain four of the most used revenue streams for batteries.

3.3.1 Capacity Market

The Capacity Market was introduced by the government to secure energy supply and avoid the possibility of blackouts. CM participants present their assets and they are paid to make sure they are available when the system goes under a stress event. With the assets presented, CM does capacity auction where the price is set and the asset's owners who are successful in the auction sign a Capacity Agreement (National Grid 2022). This agreement confirms the payment and the capacity market obligations. These contracts have a duration of 1-15 years and they are awarded 1-4 years in advance. The payments are based on capacity in £/kW/year and they are de-rated based on some criteria, which will be further analysed in Section 4.2.1.

3.3.2 Wholesale Market

Wholesale Market is a platform where generators and retailers can buy and sell power to meet demand. UK's wholesale market is further explained in Section 2.5.

3.3.3 Balancing Mechanism

BM is the principal mechanism used to balance supply and demand in real time. It is used by the TSO of Great-Britain, National Grid, to ensure this balance is maintained in the system in each trading period (Kyos Balancing Mechanism). It reacts in real time between gate of closure of the Intraday Market and the delivery window.

The function of the BM is to flow information and data between the TSO and the participants of the market. That is because when there is a mismatch between generation and demand, the TSO needs to accept, from a market participant, a bid or offer to balance and increase or decrease supply. This is done in real time to keep the system balanced and it follows this process:

1. Each generation participates with its Balancing Mechanism Units. They need to provide detailed technical specifications and capabilities.
2. Each generator sends their bids into the day-ahead market and after the auctions results, it is known which have been accepted.
3. After that, during the intraday trading market, market participants exchange power with their bids and offers. This allows to readjust their offers and make their assets more profitable.
4. After trading is done and before the gate closure, the dispatch power is sent to the TSO. This information contains the production levels in MW at each half-hour.
5. After gate closure, the TSO has to maintain the balance by making generators adapt their production based on their capabilities. All the assets present as BM need to ensure that their BMUs can produce the required level of output to keep the balance.

One important difference between the Balancing Mechanism and the Wholesale Market is that in the first one, participants are 'paid as bid' while in WM participants are paid the marginal price of the energy provider (Kyos Balancing Mechanism).

3.3.4 Ancillary Services

Ancillary services are in charge of maintaining the grid requirements. They provide secondary balancing in less than minutes response. These services are contracted in advance and the new ones are operating closer to real time. Dynamic Containment is a new ancillary service that has potential for batteries and will be further analyzed in Section 4.2.3.

From all of the revenue streams, we will analyze current and future status of each of the streams, study the role of the battery and see if requirement can be met in order to make batteries profitable.

Chapter 4

Analysis and Results

4.1 Price volatility analysis

4.1.1 Historical prices spread

The growth in renewable penetration will increase the market volatility. Requirements for the system will also increase and batteries are a well suited technology to solve these problems.

Much of the price volatility is caused because dependency on thermal units is being reduced. Current grids are design for synchronous generators and these are easier to manage to stabilize the grid. With the high penetration of renewables, transmission lines have been highly congested all of this contributing to higher price volatility.

The raw data to do this volatility analysis was taken from the terminal Bloomberg (BloombergNEF 2021). Figure 4.1.1 shows the Day-Ahead Power prices in the UK. Showing the spread between the maximum and minimum price for each day from 2018 to 2022. From this, it can be seen that from the end of 2020 prices have not only gone up but also volatility and spread between max and min have also increased notably.

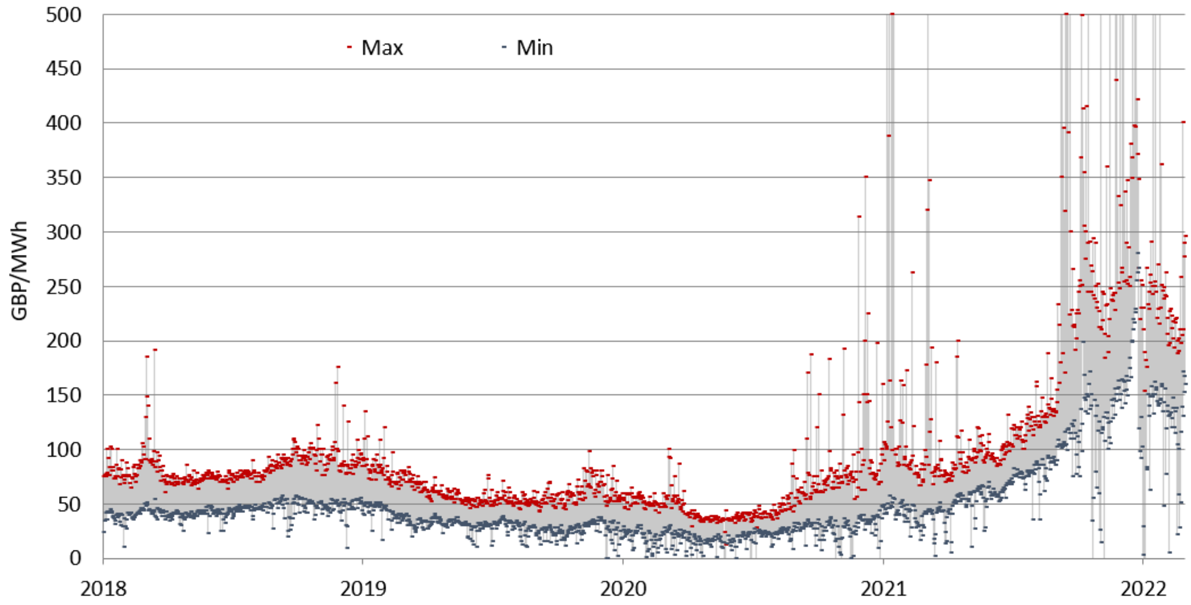

Figure 4.1.1: *EPEX Day-Ahead Power Prices in UK from Jan. 2018 to June. 2022*

Figure 4.1.2 zooms in to the months and years where the spread of prices are higher. The volatility analysis will be focused on this months.

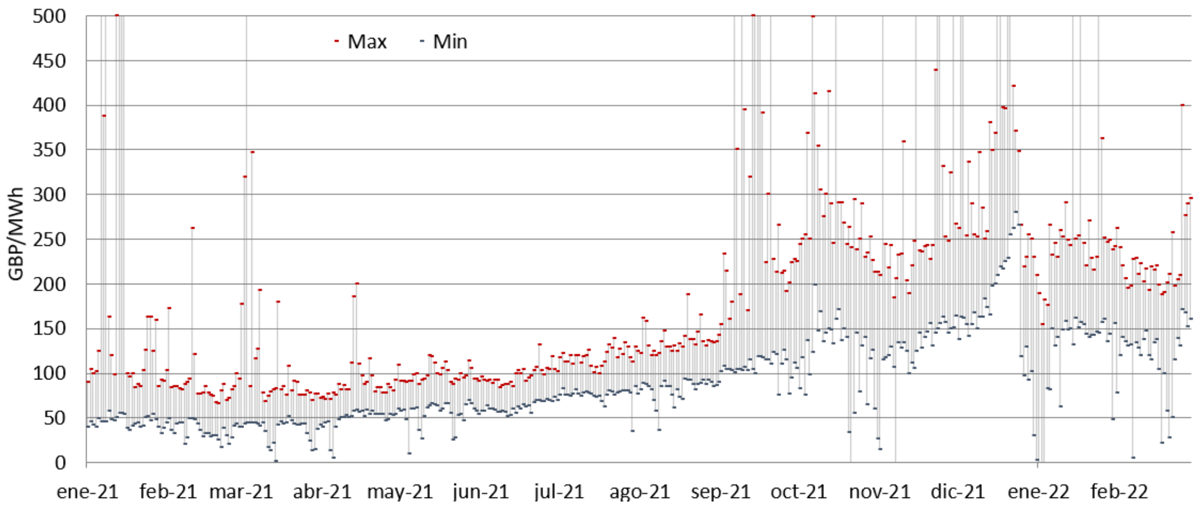

Figure 4.1.2: *EPEX Day-Ahead Power Prices in UK from Jan. 2021 to Feb. 2022*

4.1.2 Volatility calculation

Volatility is a statistical measure that represents how prices swing around the average price of a sample. The higher the value of volatility the riskier is the price considered because is less predictable. So volatility can also refer to the amount of risk or uncertainty of a certain value.

There are multiple ways to measure it, but the most common is calculating the standard deviation. This statistical measure gives the dispersion of values by giving a range within the mean value where most values of the samples can be found (Hayes 2021). Standard Deviation is the square root of the sum of squared differences from the mean all divided by the amount of samples.

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \mu)^2}{n}} \tag{4.1}$$

For this thesis, the volatility (standard deviation) is calculated for all years where we had raw data. In Appendix 5.0.1 we can find the values of volatility from 2017 to 2022. For the sake of this analysis we are going to focus on the last three years (2020, 2021 and 2022 until the month of June).

After calculating the standard deviation of each month of the multiple years, in the following Figures 4.1.3, 4.1.4 and 4.1.5 the maximum prices of each month are plotted in dark green, the minimum prices in blue and the average price of the month in red. The volatility value (which is a range within the average where most prices are found) is shown in gray.

Year 2020

As can be seen in Figure 4.1.3, in 2020 price spread was small. The maximum price was 350 GBP/MWh and the minimum -38,8 GBP/MWh. The highest deviation standard value stands at 24,42 in December 2020. It can be seen that the spread of prices was increasing in the last months of the year, a trend that in 2021 was accentuated. Table 4.1.1 shows the values calculated for the analysis of this year.

Table 4.1.1: Volatility values in 2020

Year	**Month**	**Average**	**Var. Avg.**	**Max**	**Min**	**dS**	**Var. dS**
2020	ene-20	35,72	-9%	65	7,25	9,11	-21%
2020	feb-20	30,62	-14%	59,62	-4,33	10,46	15%
2020	mar-20	31,67	3%	99,9	1,43	11,35	9%
2020	abr-20	24,18	-24%	43,41	-19	10,15	-11%
2020	may-20	22,17	-8%	43,22	-38,8	11,52	13%
2020	jun-20	26,49	19%	42	-17,65	8,59	-25%
2020	jul-20	29,45	11%	48,99	-16,89	8,65	1%
2020	ago-20	36,28	23%	99,4	7,63	10,66	23%
2020	sep-20	43,78	21%	187,1	11,3	15,00	41%
2020	oct-20	43,41	-1%	183,2	-7,18	15,65	4%
2020	nov-20	44,01	1%	313,45	-4,36	20,47	31%
2020	dic-20	54,98	25%	350	-8,28	24,42	19%

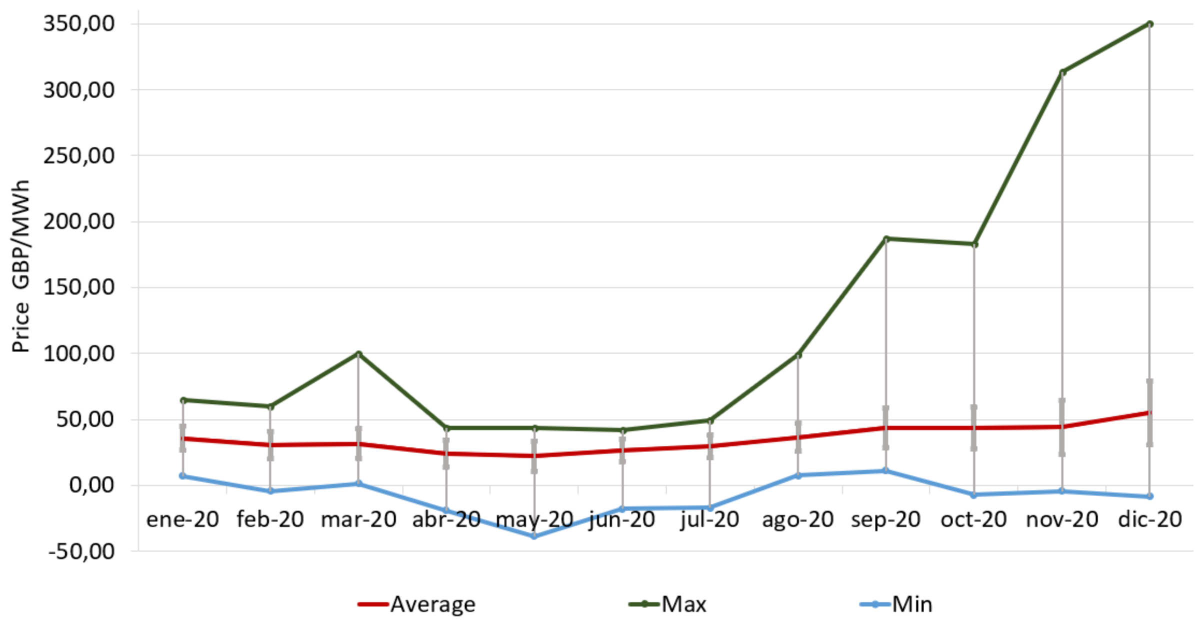

Figure 4.1.3: *Volatility values in 2020*

Year 2021

As can be seen in Figure 4.1.4, at the end of 2021 price spread increased drastically, starting in September. The maximum price of the year was 1860 GBP/MWh and the minimum -6,7 GBP/MWh. The highest deviation standard value stands at 174,13 in September. Spread of prices increased drastically compared to 2020, comparing year maximums there was an increase of 413%. Table 4.1.2 shows the values calculated for the analysis of this year.

Table 4.1.2: Volatility values in 2021

Year	**Month**	**Average**	**Var. Avg.**	**Max**	**Min**	**dS**	**Var. dS**
2021	ene-21	79,15	44%	1500	33	98,08	302%
2021	feb-21	53,82	-32%	262,5	16,5	17,75	-82%
2021	mar-21	56,81	6%	683	1,9	34,00	92%
2021	abr-21	64,85	14%	200	5	18,96	-44%
2021	may-21	73,79	14%	120	10	15,38	-19%
2021	jun-21	77,88	6%	132	52	12,50	-19%
2021	jul-21	92,80	19%	139	35	14,55	16%
2021	ago-21	106,86	15%	187,5	35,65	18,97	30%
2021	sep-21	187,87	76%	1860	75	174,13	818%
2021	oct-21	181,23	-4%	1010	-6,7	65,72	-62%
2021	nov-21	187,97	4%	1612,5	-4,3	110,73	68%
2021	dic-21	246,28	31%	1500	2,9	123,26	11%

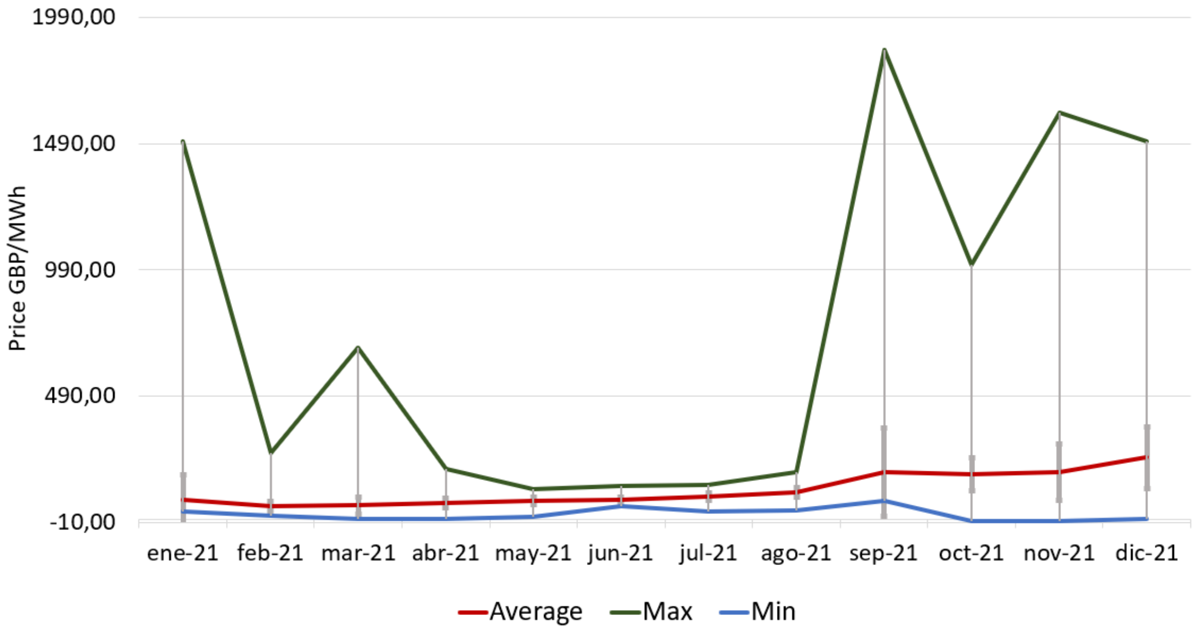

Figure 4.1.4: *Volatility values in 2021*

Year 2022

As can be seen in Figure 4.1.5, the year started with high price spread but from April on, it decreased. The maximum price of the year until June was 1000 GBP/MWh and the minimum -24,9 GBP/MWh. The highest deviation standard value stands at 87,63 in January. Even if this last months volatility has decreased, it is still higher than the previous years. Comparing to 2020, the highest deviation standard value was -259% from the highest deviation standard value of 2022. Table 4.1.3 shows the values calculated for the analysis of this year. It is expected that with the increase of renewable penetration, volatility will keep increasing as is explained in the next Section 4.1.3.

Table 4.1.3: Volatility values in 2022

Year	Month	Average	Var. Avg.	Max	Min	dS	Var. dS
2022	ene-22	182,98	-26%	1000	-24,9	87,63	-29%
2022	feb-22	164,26	-10%	400	5	41,91	-52%
2022	mar-22	251,38	53%	702,5	79	83,69	100%
2022	abr-22	177,23	-29%	319,4	34,8	45,54	-46%
2022	may-22	127,69	-28%	235,2	20	39,67	-13%
2022	jun-22	145,27	14%	270,35	0,44	40,71	3%

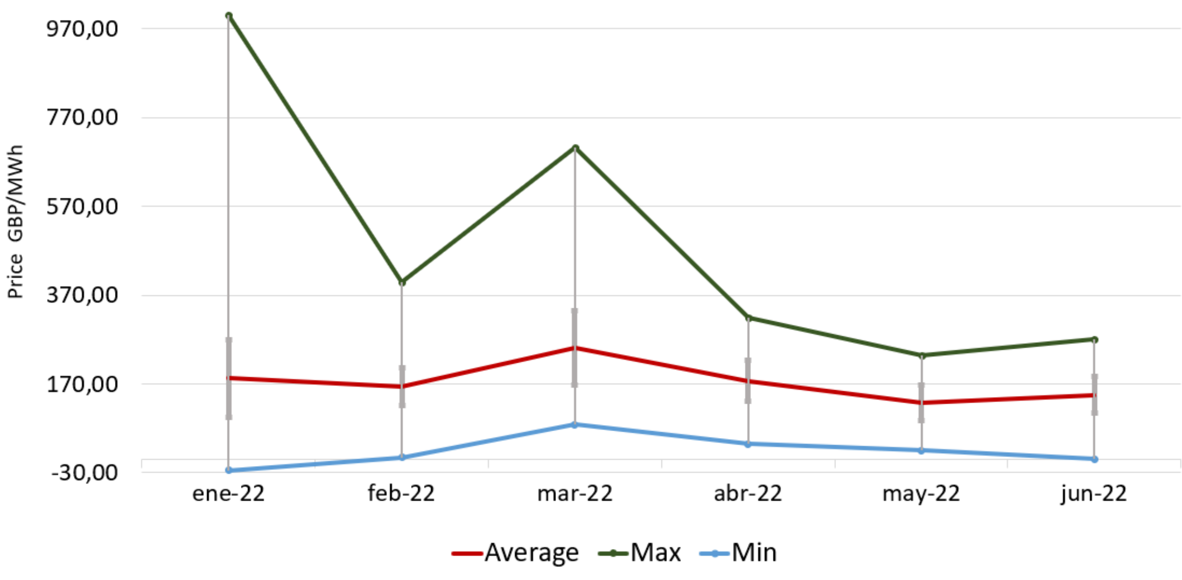

Figure 4.1.5: *Volatility values in 2022*

4.1.3 Correlation with renewable penetration

Volatility has increased because of higher renewable penetration. For two main reasons, one is the congestion of transmission lines because of all the new capacity installed. Secondly, because dependency reduction on synchronous generators thermal units. That is the reason why the planned growth of generation and the reduction of thermal units is expected to keep increasing price volatility and batteries could be a great system for stabilizing the prices.

It is important to mention that volatility not only depends on renewable penetration, prices are subjected to many parameters such as generation, weather conditions, political situation, etc. Said this, in Figure 4.1.6 we can still see a correlation between the renewable generation (wind and solar) over the years and the increasing trend of volatility. Year 2022 is an estimated generation value based on the current installed capacity. In the graph is also plotted the trend line for both parameters drown so correlation can be seen more easily.

Correlation coefficient between both values is calculated. The closer it is to 1 the more correlated are the two parameters. In this case, standard deviation and renewable generation are correlated by a coefficient of 0.81 meaning that both are increasing simultaneously at a similar pace.

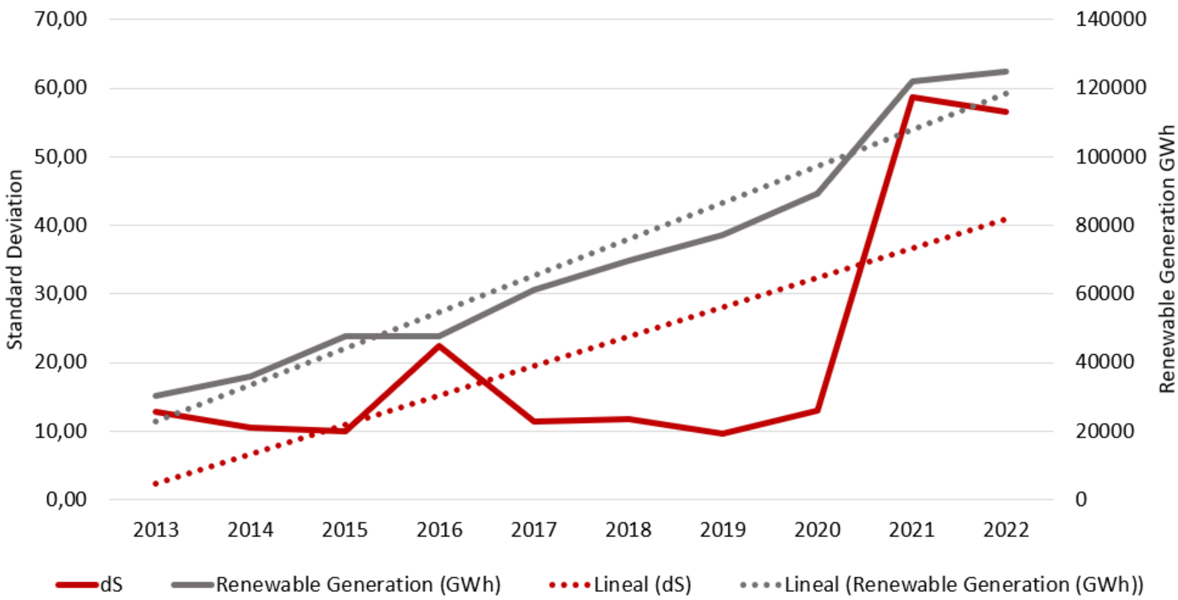

Figure 4.1.6: *Trend of standard deviation and renewable generation from 2013-2022 (gov.UK 2021; UK 2022)*

The same comparison is done in Figure 4.1.7 with renewable installed capacity (wind and solar) in GW and Standard Deviation. In this case correlation factor is still positive, which means that installed capacity and volatility are correlated, but it has a lower value of 0.51.

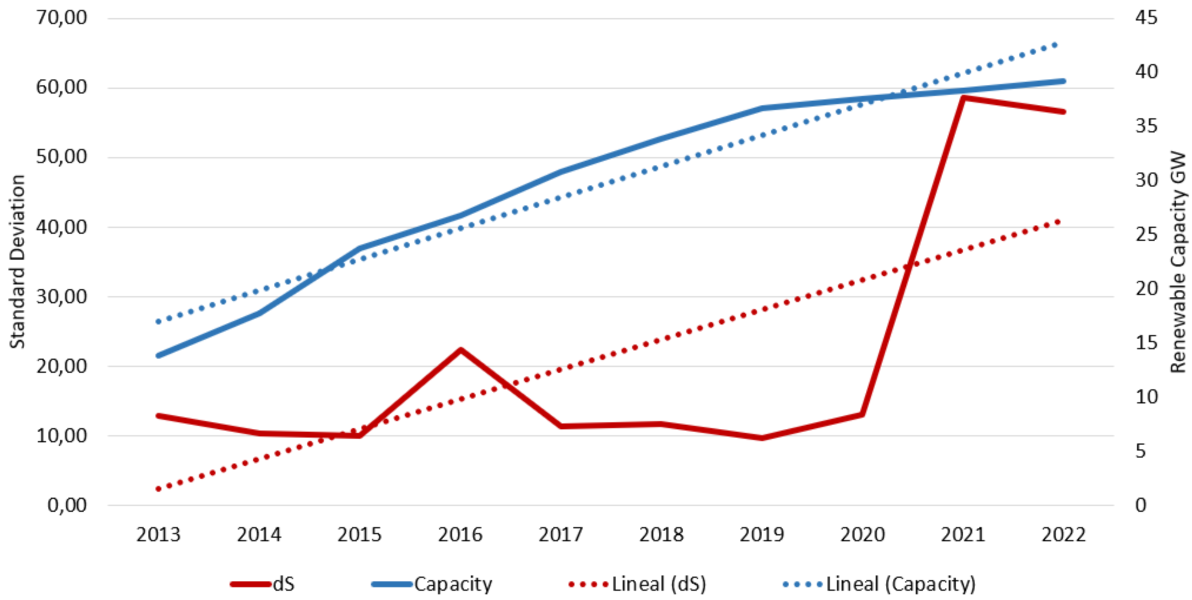

Figure 4.1.7: *Trend of standard deviation and renewable installed capacity from 2013-2022 (gov.UK 2021; BloombergNEF 2021)*

Appendix 5.0.1 shows Table .0.4 where there are the detailed values of the correlation analysis.

As mentioned in Section 2.6, UK has the target of installing 40 GW of offshore wind, 5 GW of hydrogen and more than 6 GW of storage in 2030. This planned renewable generation will most likely make volatility increase and provide batteries a source of revenue in price arbitrage.

4.2 Analysis of revenue streams

4.2.1 Capacity Market

The Capacity Market looks promising for battery integration in the future. But currently, batteries are heavily de-rated because of their short duration and their usefulness for security of supply in long term, specially 1 and 2 hours duration batteries (Aurora 2022).

The UK uses the following formula to put a price on CM services:

$$AnnualCMpayment = [AuctionClearingPrice]x[DeratingFactor]x[Capacity] \tag{4.2}$$

Where,

Annual CM payment is in £

Auction clearing price in £/MW

De-rating factor in %

Capacity in MW

The higher the de-rating factor in percentage, the higher the total annual payment will be. Currently de-rating factors are around 20% for 1 hour batteries and 40% for 2 hours battery which comparing to a OCTGT plant is really small since they have 95%. Coal and biomass have de-rating factors of 89% and Nuclear around 80%. Storage is far from these old technologies in terms of getting high revenue from Capacity Market.

Figure 4.2.1 shows the outlook of prices for CM. Prices are expected to remain high in the next decade as new technologies are coming to replace fossil fuels and meet the demand. In the mid 2030s prices will rise because of the retirement of nuclear and CCGT capacities. In general, more renewable incorporation will drive to increasing CM prices because these technologies bring instability to the grid.

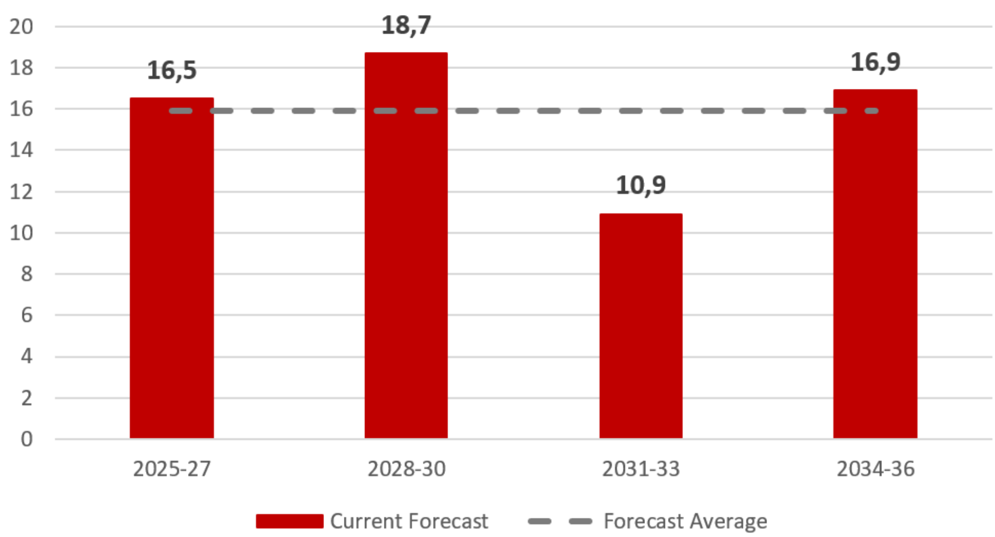

Figure 4.2.1: *Average CM forecast prices in £/kW (Aurora 2022).*

4.2.2 Wholesale Market

In this platform where power is sold and bought, price volatility plays a big role as is key for battery margins. Storage technology, such as batteries, are a great revenue stream for price arbitrage. Batteries can strategically operate to benefit from price differences during the day. This technology is able to store power when prices are low or even negative price intervals and sell it once prices are high, so their profit can increase. But in order for batteries to make money from energy arbitrage, they need enough market price volatility.

As mentioned in Section 4.1, penetration of renewable energy increases the price volatility due to the intermittence and high dependency on weather conditions and thus help the revenue of batteries to also increase. A forecast study on volatility's future tells us that the frequency of low prices, lower than 20£, is expected to increase by 28% between 2021 to 2050. The frequency of high prices, higher than 80£, is expected to increase by 18% between 2025 and 2050. This increase in frequency for low and high prices will create an increase in price volatility. Figure 4.2.2 shows analysis of frequency distribution of electricity prices in UK based on data provided by (Aurora 2022). It shows how, over the years, the frequency of highest (green) and lowest prices (gray) keep increasing.

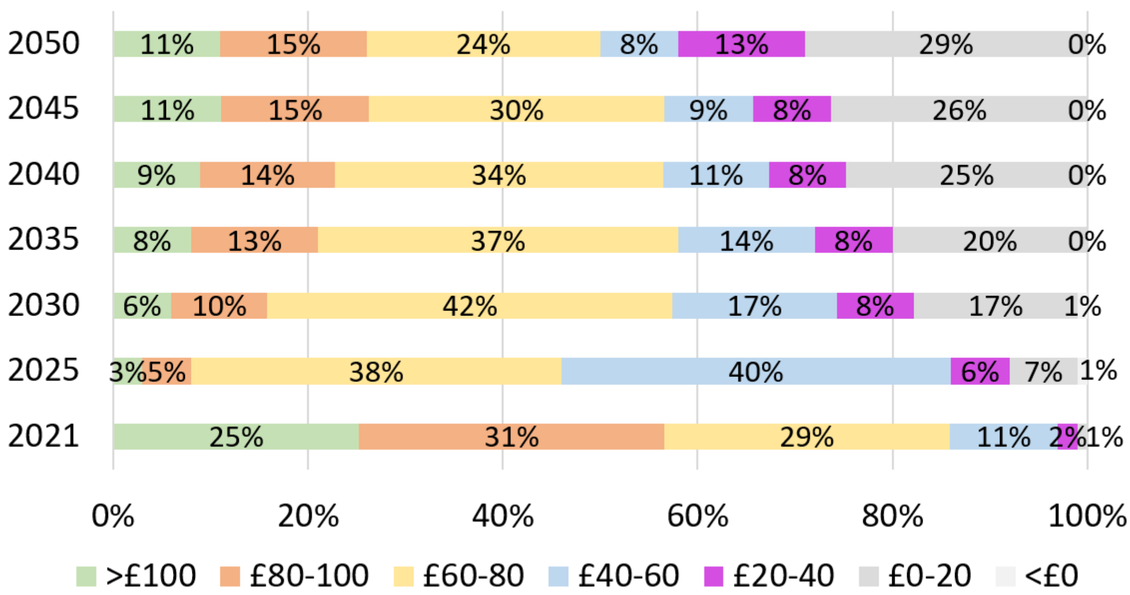

Figure 4.2.2: *Frequency distribution of the electricity price from 2021-25 (Aurora 2022)*

4.2.3 Ancillary Services

Dynamic Containment

DC is a new fast-acting ancillary service that acts post-fault in order to keep the frequency of the system in the range of +/-0.5Hz. It activates in case of a sudden demand or generation loss when frequency is out of the limits, which is 0.2 Hz below or above in the UK grid. It is designed to operate proportionally and quickly. National Grid purchased 197 MW of dynamic containment capacity in October when it was expecting 500 MW. In January this year, the average daily capacity bought was 333 MW but it was hoping to buy around 700 MW. As can be seen by these numbers, this service is still not very common and not reaching the goals of National Grid.

Although dynamic containment has huge potential for battery projects, battery operators have not entirely latched to it yet. This is because technical requirements for this service can be hard and daunting. Battery operators have to provide the ESO with operational data on a second-by-second timing as well as performance reports at resolutions of 20Hz (National Grid 2022). This lack of capacity being tendered has made National Grid ESO take almost all the capacity and currently just 1% of daily capacity is rejected because of the high cost.

DC pricing worked the following way. National Grid was paying around 17£ per MWh of capacity, which compared to the price they were getting in other frequency services, meant they were getting a premium of 40%. Mid 2021, ESO announced the pricing to be as pay-as-clear in a more granular way dividing the day into periods (National Grid 2022).

4.3 Investment case

In Section 4.1 it has been demonstrated how batteries can use price arbitrage as a revenue stream thanks to increase in prices' volatility. In this section a small investment case is done in order to check if is profitable to invest in large-scale batteries in the UK to use them for price arbitrage.

The analysis is done following this simple model:

First, the CAPEX of a battery system is considered. The cost of developing grid-scale batteries is made up of different components and these values were obtained from a report made by Aurora Energy Research (Aurora 2022). Table 4.3.1 shows the breakdown of costs for a large-scale Li-ion battery in 2022.

Table 4.3.1: CAPEX breakdown costs Li-ion battery

Distribution of costs	**Amount**	**Units**
Battery System	300	GBP/kW
Inverter	90	GBP/kW
Other Electircal	80	GBP/kW
EPC Costs	75	GBP/kW
Connection Costs	65	GBP/kW
Development costs	60	GBP/kW
TOTAL	**670**	**GBP/kW**

Table 4.3.2 shows, for this specific investment case, the data that has been considered for the battery system.

Table 4.3.2: Battery data assumed

Data	**Amount**	**Units**
Capacity	20	MW
Charge/Discharge	1	h/cycle
Cycles per day	1,5	cycles/day
CAPEX	670	GBP/kW
Life time	15	years

In order to calculate the amount of revenue that can be obtain from price arbitrage, the spread (difference between maximum and minimum price) is calculated for everyday from 2018 to 2022. The prices' spread is calculated because it is assumed that the battery is discharged when prices are the highest and charged when prices are the lowest, making the difference the amount of revenue that can be obtained. Tables .0.5, .0.6, .0.7, .0.8 and .0.9, in Appendix 5.0.1 shows the value of the spread for the whole time period mentioned.

For this investment case, we considered different spread values (from best to worse) and compared the solutions. The scenarios chosen are:

- **Case 1:** MAX SPREAD (2018-22). This case is the most optimistic since it is taking the maximum spread value from the last 5 years.
- **Case 2:** AVERAGE SPREAD (2021-22). This case is similar to the previous one but taking the maximum spread value from the last and actual year.
- **Case 3:** AVERAGE SPREAD (2018-22). This case is more limiting since it is taking the average of all spread values from the last 5 years.
- **Case 4:** MIN SPREAD (2012-22). This case is the most pessimistic since it takes the minimum spread value from the last 11 years.

With these hypothesis and spread values, the revenue we can obtain from price arbitrage is calculated. It is done by multiplying the spread value by the capacity of the battery, the charge/discharge time, the number of cycles per day, the number of days in a year and the years of life time of the battery. It is important to mention that this is a simple investment case and some factors such as efficiency, degradation, etc. are not taken into account to simplify the model. Table 4.3.3 shows the revenue in GBP that batteries can obtain from price arbitrage. In the same table, we calculated if it is profitable to invest on this storage systems by calculating the difference between the investment cost and the revenue. The CAPEX is calculated by multiplying the total value on Table 4.3.1 by the total battery capacity. Finally if profit is negative means that the revenue is higher than the CAPEX over the lifetime of the battery. That means we are making money by investing on the battery. If it is positive, means the CAPEX cost is to big to create revenue for the battery owners. In the second case, government should invest and implement new regulation so battery investors receive support to develop this needed technology in the country.

Table 4.3.3: Results for large-scale battery investment case

CASES	SPREAD (GBP/MWh)	REVENEU (GBP)	PROFIT (GBP)	Invest?
Case 1	1741	285959250	-272559250	YES
Case 2	141	23175365	-9775365	YES
Case 3	66	10878647	2521352	NO
Case 4	11	1859310	11540690	NO

Figure 4.3.1 shows the revenue value for each of the cases in gray and the value of the capex in GBP in red, with is 13.4M GBP.

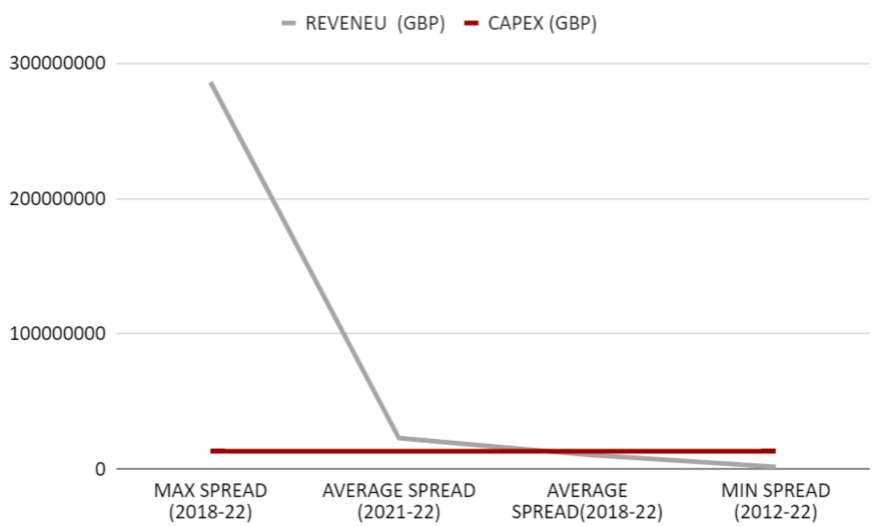

Figure 4.3.1: *Comparison of CAPEX and revenue value for each spread of the investment case.*

It is worth reminding that these values are high because they are considered for the whole lifetime of the battery and with a constant spread value, which is not the case for the whole lifetime of the battery. From Figure 4.3.1 we can see that only in the two first cases is profitable to invest in a battery system. Case 2 is the most realistic case since is taking the average spread of two last years. Calculating the limit of which profit would become positive is at a value of a spread of around 81,58 GBP/MWh meaning that this is the minimum spread value for which the investment of a battery system would be profitable for any private owner.

4.4 SWOT Analysis

SWOT stands for Strength, Weakness, Opportunity and Threat. This analysis was done to evaluate the competitive position of large-scale batteries in the UK. External and internal factors as well as all present and future potential are assessed to have a fact-based analysis and give fresh perspectives giving room for new ideas.

STRENGTHS

1. Stabilize the electricity grid appeasing renewable technology intermittence.
2. Suitable for ancillary services.
3. Fast response time, only few seconds to start.
4. Batteries are a proven technology.

WEAKNESSES

1. Difficult to meet with technical requirements asked from National grid.
2. Battery degradation and limited lifetime.
3. Short charge and discharge cycles.
4. Strong sensitivity to extreme temperatures.
5. Technology available for everyone (no need of expertise).

OPPORTUNITIES

1. Lower cost of network development.
2. Strong renewable and storage technology government goals.
3. Opportunity of revenue with price arbitrage.
4. Increase grid stability of the island.
5. Act as Dynamic Containment which gets paid a premium of 40% compared to other services.
6. Favor the penetration of renewable projects.

THREATS

1. Limited capacity once they solve the problem.
2. Concerns about possible ecological damage when recycling it.
3. High CAPEX.
4. Possibility of emergence of new technologies more suitable for certain applications.

4.5 Success case

4.5.1 Hornsdale Power Reserve in Australia

Australia currently has one of the world's biggest large-scale batteries in the state of South Australia. Hornsdale Power Reserve is a 150 MW/ 194 MWh grid connected storage system. The contract to build the battery was won by Tesla in 2017 but the battery is now owned by Neoen (Kolodny 2021).

In Australia the main revenue source for batteries has been providing FCAS, specially when there has been grid events and the prices have gone very high. Previously in South Australia these services were provided only by 3 companies using gas generators and they charged pretty high prices. Batteries are much better at providing these services (faster, more accurate, don't need to burn gas) and so when the Tesla battery (Hornsdale) was installed it was able to take a large amount of these revenues. Since it was installed it has basically made it's money back, with large amounts earned during a few key events in SA.

For example, in 2018, Australian Energy Marker Operator called for generators in SA to provide 35 MW of FCAS. This need for network services are usually asked when there is a system fault or a planned maintenance between Victoria and SA interconnector. When this happens, market prices go into orbit, but in this case the newly installed Tesla battery bid in the market to ensure prices kept reasonable. This helped maintain the prices at around 270 AUD/MW instead of jumping up the prices of around 12000 AUD/MW. That is because before, big gas generators where charging ten times the cost of the price of this services, making around 7 AUD million a day (Parkinson 2018).

In 2019, the Hornsdale Power Reserve made a revenue of about $21M of which $41m was for FCAS services. This excludes the revenue from charging component, that was $10.5M but with a cost for charging of $3M.

Chapter 5

Conclusions

The main purpose of this thesis was to analyse how companies can monetize batteries to help stabilize the electricity grid and price of a country and to study if is profitable to invest in large scale battery projects in the UK. We have seen how renewable energy's boom has make grids unstable and prices very volatile and how new technologies such as batteries can help cope with this challenge and move forward with the energy transition.

A study of UK's power market has allowed me to understand the background of the country and what is the current situation. How is the electricity profile, how it is sold, how have the prices evolved over the years in the wholesale markets and what are the plans for the country to achieve net-zero greenhouse emissions are all important to proceed studying the possible revenue streams for this kind of technology.

We have seen what is the current battery capacity and owners and what are the possible revenue streams under the current country's regulation. Capacity Market looks promising for battery integration in the future, but after the research we have reached to the conclusion that current de-rating factors are really low for this technology which prevents them to compete with other generators such as coal or nuclear. The use of batteries in FCAS is one of the interesting revenue sources because of the high prices that the regulator is paying. The problem with current FCAS such as Dynamic Containment is that the technical requirements are hard for batteries to meet and owners have not entirely latched into it yet. One problem with this going forward is that the required total MW of FCAS are not very large, and so as more batteries come online, this requirement should be met more easily and prices will drop. This leaves arbitrage.

For price arbitrage a whole volatility study was done for this thesis. We can conclude that volatility in the UK is high enough for batteries to make revenue and it has future opportunity as well since the research has shown that price volatility will increase as more renewable energy will enter since both variables are highly correlated. First we studied that there is possibility of revenue from battery implementation as arbitrage, but after the investment case analysis, we calculated if it is profitable to invest on it. We have seen that for certain levels of spread in prices, it is worthy to build large-scale batteries in UK as of now. But again the problem here is that as more batteries come online this arbitrage value will drop, as they storage should help to reduce volatility. Recently the large volatility in prices in UK have meant there has been some good arbitrage value available for batteries, but it is not certain how long this will last.

We can reach to the conclusion that batteries in the UK are a good opportunity. But we have also seen some limitations, the SWOT study has allowed to see an overall comparison of pros and cons. One more advantage added to the SWOT analysis is that companies that currently have a Trading Desk have the ease to be able to manage batteries like their other assets.

This project has allowed me to understand and learn about energy markets and battery's role on it. I have learnt the importance of renewable technology such as batteries and the importance of country's regulation to help with this transition and evolve into a cleaner energy world.

5.0.1 Future work

This results can lead to further analysis in the future. Some revenue streams seem more promising than others. From one side, price arbitrage revenue is highly dependent on the spread value of prices between maximum and minimum. Although it is currently the best revenue stream, price arbitrage is highly unpredictable and only relying on this stream is not the most safe investment. But we have seen some other promising opportunities for batteries. There is possibility for them to work as Ancillary Services or participate in Capacity Market if regulation changes and batteries are less de-rated. It is important to mention how regulation plays a big role on further evolution of this technology in the country. UK's electricity regulator and the government need to create new policies to encourage the implementation of batteries and help owners make money from the multiple revenue streams mentioned in this thesis.

This research leaves place for further analysis on the different ways to monetize batteries. More in depth investment cases could be done for the different revenue streams. It is worth mention that this type of research needs to be updated since technology and regulation evolve really fast and those changes could encourage companies to invest on batteries.

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Appendix

Table .0.1: Volatility analysis from 2017-2018

Year	Month	Average	Var. Avg.	Max	Min	dS	Var. dS
2017	ene-17	52,85		146,12	28,87	14,81	
2017	feb-17	49,19	-7%	105	22,19	11,22	-24%
2017	mar-17	41,92	-15%	124,15	12,3	12,64	13%
2017	abr-17	41,07	-2%	108,75	23,93	10,01	-21%
2017	may-17	41,11	0%	82,83	22,48	9,49	-5%
2017	jun-17	37,88	-8%	132,77	1,57	11,28	19%
2017	jul-17	40,82	8%	115	14,99	12,08	7%
2017	ago-17	42,43	4%	78,07	9,54	10,21	-15%
2017	sep-17	45,98	8%	149,92	14,98	12,99	27%
2017	oct-17	45,71	-1%	89,4	5	11,33	-13%
2017	nov-17	50,24	10%	99,98	24,15	9,96	-12%
2017	dic-17	54,79	9%	98,75	4,56	10,98	10%
2018	ene-18	49,80	-9%	101,79	10,1	11,00	0%
2018	feb-18	51,15	3%	105	27,05	11,00	0%
2018	mar-18	57,02	11%	191,55	34,99	17,42	58%
2018	abr-18	50,70	-11%	85,95	25	9,99	-43%
2018	may-18	53,29	5%	80	22,41	10,10	1%
2018	jun-18	53,94	1%	80	24,43	9,76	-3%
2018	jul-18	56,87	5%	89,99	35,02	10,03	3%

Table .0.2: Volatility analysis from 2018-2020

Year	Month	Average	Var. Avg.	Max	Min	dS	Var. dS
2018	ago-18	60,59	7%	93	26,59	10,42	4%
2018	sep-18	66,47	10%	110	20	13,34	28%
2018	oct-18	64,31	-3%	122,54	35,75	12,13	-9%
2018	nov-18	61,94	-4%	175	34,57	13,59	12%
2018	dic-18	62,63	1%	140	9,09	12,03	-11%
2019	ene-19	60,84	-3%	134,6	16,79	12,68	5%
2019	feb-19	50,18	-18%	97,47	25,6	10,00	-21%
2019	mar-19	44,30	-12%	83,15	20	9,67	-3%
2019	abr-19	43,54	-2%	74,1	23,13	8,85	-8%
2019	may-19	41,36	-5%	64	17,26	7,85	-11%
2019	jun-19	38,63	-7%	76,12	10	8,77	12%
2019	jul-19	41,05	6%	71	14,92	7,72	-12%
2019	ago-19	38,14	-7%	61	10,4	8,96	16%
2019	sep-19	36,20	-5%	70	11,94	9,61	7%
2019	oct-19	36,87	2%	71,5	11,06	9,23	-4%
2019	nov-19	44,43	21%	98,4	16,85	10,43	13%
2019	dic-19	39,11	-12%	84,4	0	11,52	10%
2020	ene-20	35,72	-9%	65	7,25	9,11	-21%
2020	feb-20	30,62	-14%	59,62	-4,33	10,46	15%
2020	mar-20	31,67	3%	99,9	1,43	11,35	9%
2020	abr-20	24,18	-24%	43,41	-19	10,15	-11%
2020	may-20	22,17	-8%	43,22	-38,8	11,52	13%
2020	jun-20	26,49	19%	42	-17,65	8,59	-25%
2020	jul-20	29,45	11%	48,99	-16,89	8,65	1%
2020	ago-20	36,28	23%	99,4	7,63	10,66	23%
2020	sep-20	43,78	21%	187,1	11,3	15,00	41%
2020	oct-20	43,41	-1%	183,2	-7,18	15,65	4%
2020	nov-20	44,01	1%	313,45	-4,36	20,47	31%
2020	dic-20	54,98	25%	350	-8,28	24,42	19%

Table .0.3: Volatility analysis from 2021-2022

Year	Month	Average	Var. Avg.	Max	Min	dS	Var. dS
2021	ene-21	79,15	44%	1500	33	98,08	302%
2021	feb-21	53,82	-32%	262,5	16,5	17,75	-82%
2021	mar-21	56,81	6%	683	1,9	34,00	92%
2021	abr-21	64,85	14%	200	5	18,96	-44%
2021	may-21	73,79	14%	120	10	15,38	-19%
2021	jun-21	77,88	6%	132	52	12,50	-19%
2021	jul-21	92,80	19%	139	35	14,55	16%
2021	ago-21	106,86	15%	187,5	35,65	18,97	30%
2021	sep-21	187,87	76%	1860	75	174,13	818%
2021	oct-21	181,23	-4%	1010	-6,7	65,72	-62%
2021	nov-21	187,97	4%	1612,5	-4,3	110,73	68%
2021	dic-21	246,28	31%	1500	2,9	123,26	11%
2022	ene-22	182,98	-26%	1000	-24,9	87,63	-29%
2022	feb-22	164,26	-10%	400	5	41,91	-52%
2022	mar-22	251,38	53%	702,5	79	83,69	100%
2022	abr-22	177,23	-29%	319,4	34,8	45,54	-46%
2022	may-22	127,69	-28%	235,2	20	39,67	-13%
2022	jun-22	145,27	14%	270,35	0,44	40,71	3%

Table .0.4: Correlation study values from 2013 to 2022

Year	Standard Deviation	Renewable Generation (GWh)	Renewable Capacity (GW)
2013	12,87	30407	13,86
2014	10,41	36013	17,75
2015	9,97	47808	23,75
2016	22,38	47554	26,83
2017	11,42	61116	30,78
2018	11,73	69642	33,87
2019	9,61	77253	36,69
2020	13,00	89411	37,57
2021	58,67	121980	38,28
2022	56,52	124920,08	39,2

Table .0.5: Monthly average's spread value from 2018

Year	Month	Max	Min	Spread
2018	ene-18	101,79	10,1	44,61
2018	feb-18	105	27,05	41,29
2018	mar-18	191,55	34,99	52,90
2018	abr-18	85,95	25	33,67
2018	may-18	80	22,41	32,09
2018	jun-18	80	24,43	33,04
2018	jul-18	89,99	35,02	31,90
2018	ago-18	93	26,59	32,70
2018	sept-18	110	20	46,37
2018	oct-18	122,54	35,75	46,48
2018	nov-18	175	34,57	49,15
2018	dic-18	140	9,09	43,28

Table .0.6: Monthly average's spread value from 2019

Year	Month	Max	Min	Spread
2019	ene-19	134,6	16,79	42,22
2019	feb-19	97,47	25,6	35,74
2019	mar-19	83,15	20	36,87
2019	abr-19	74,1	23,13	26,90
2019	may-19	64	17,26	23,63
2019	jun-19	76,12	10	26,61
2019	jul-19	71	14,92	23,48
2019	ago-19	61	10,4	26,13
2019	sept-19	70	11,94	31,68
2019	oct-19	71,5	11,06	31,99
2019	nov-19	98,4	16,85	39,13
2019	dic-19	84,4	0	37,50

Table .0.7: Monthly average's spread value from 2020

Year	**Month**	**Max**	**Min**	**Spread**
2020	ene-20	65	7,25	31,50
2020	feb-20	59,62	-4,33	34,97
2020	mar-20	99,9	1,43	38,18
2020	abr-20	43,41	-19	26,05
2020	may-20	43,22	-38,8	23,76
2020	jun-20	42	-17,65	22,49
2020	jul-20	48,99	-16,89	20,23
2020	ago-20	99,4	7,63	28,38
2020	sept-20	187,1	11,3	45,28
2020	oct-20	183,2	-7,18	54,62
2020	nov-20	313,45	-4,36	66,53
2020	dic-20	350	-8,28	80,28

Table .0.8: Monthly average's spread value from 2021

Year	**Month**	**Max**	**Min**	**Spread**
2021	ene-21	1500	33	230,82
2021	feb-21	262,5	16,5	57,26
2021	mar-21	683	1,9	91,97
2021	abr-21	200	5	44,55
2021	may-21	120	10	44,20
2021	jun-21	132	52	35,48
2021	jul-21	139	35	43,32
2021	ago-21	187,5	35,65	54,57
2021	sept-21	1860	75	342,39
2021	oct-21	1010	-6,7	191,19
2021	nov-21	1612,5	-4,3	264,48
2021	dic-21	1500	2,9	268,79

Table .0.9: Monthly average's spread value from 2022

Year	Month	Max	Min	Spread
2022	ene-22	1000	-24,9	188,38
2022	feb-22	400	5	110,81