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

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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.

I. 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 [1]. Currently, solar photovoltaic has close to 1 TW of installed capacity, wind 837 GW and hydropower 1330 GW [2].

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 paper 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. 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 success case of battery implementation in Australia is explained for further reference. The research is finished with conclusions and future work.

II. POWER MARKET

A. Introduction to UK

The United Kingdom (UK) is a country in north-western Europe. The country 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. Population of the country in 2021 was estimated to be around 67.65 million [3]. Referring to economics, Gross Domestic Product, GDP in 2021 was estimated 3,108.42 billion USD [1] 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.

B. Electricity profile

1. Capacity and Generation

The installed electricity capacity in 2020 was 100.73 GW of which 47.27 GW was from renewable sources. The capacity distribution is 33% natural gas, 24% wind, 13% solar, 13% bio-fuels, 9% nuclear, 5% oil, 3% others. [3]

The total generation of the country in 2020 was 284.3 TWh. 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. 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 and lower renewable generation due to weather conditions [4].

2. Consumption

Electricity consumption in UK is around 305 TWh/year. The use of electricity declined a 28% from 2005 to 2020 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 [5]. 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 [1].

3. Interconnections

As of 2021, National Grid operates 5 interconnectors with Europe:

- UK with France (IFA1): a 70km 2000MW HVDC [6].
- UK with France (IFA2): a 240km 1000MW HVDC [6].
- UK with The Netherlands (BritNed): a 260km 1000MW HVDC [7].
- UK with Belgium (Nemo Link): a 140km 1000MW [8].
- UK with Norway (NSL): a 720km 1400MW [9].

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 [4].

C. Power Market structure and players

The Electricity Act in 1989 created major changes in UK's electricity sector. Deregulation means that utility companies must divest all ownership and different utilities are responsible for distribution, operation, transmission and billing the customer. Deregulation allowed customers to choose energy supplier and the competition between companies eventually led to more competitive prices. [10].

Figure 1 shows the current power market distribution with the responsibility of each key player.

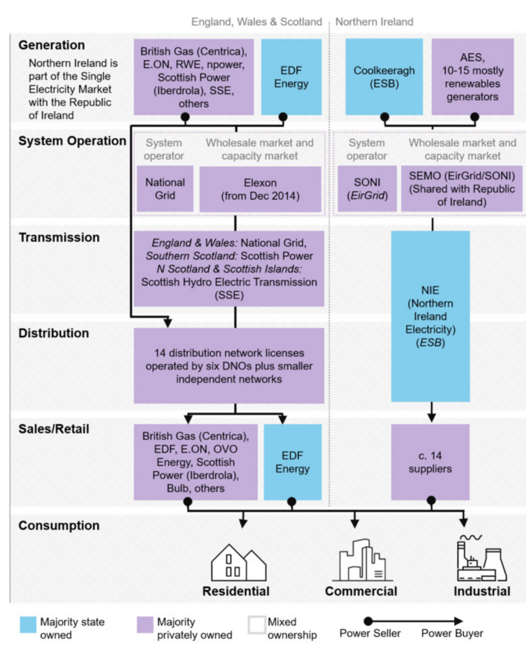

Figure 1: *UK Power Market structure and players [3].*

Electricity market has become very diverse with over 38 power producers operating and a fast growing number of small power generators. 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.

D. 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. Currently, there are two markets operating, NORD POOL and EPEX. The total volume traded in the first market in 2021 was 963 TWh, of which more than 15% was traded in GB, that is 147.3 TWh [11]. 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 [12]. Both markets operate in many countries in Europe and have similar DAM prices.

Taking as reference the prices in the EPEX market, Figure 2 shows the evolution of the baseload prices in the UK. 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.

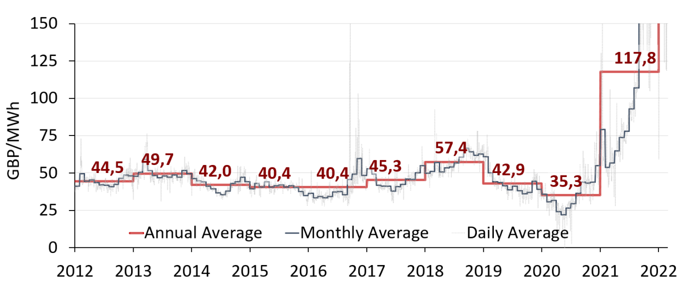

Figure 2: *EPEX Baseload Prices in UK from 2012 to 2022*

E. 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 [13].

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 [3]. 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.
- By 2030, end the sales of petrol and diesel vans and cars. In 2035 all vehicles should be 100% zero emissions.
- Both onshore wind and solar are re-admitted to the next CFD auction.
- 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.
- There is a coal phase-out policy in force, with a deadline to end coal in power generation from October 2024.

III. BATTERIES STATE OF THE ART

A. Regulation

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 [14].

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) [15]. 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 [16].

B. Active regulatory programs

These are some of the active regulatory programs that Ofgem is leading which are not specific for batteries but they can participate:

- **Dynamic Containment** ancillary services to boost the grid's resilience. Tenders for this service run every day of the week to help with frequency control [17].
- **Dynamic Regulation Auction** a pre-fault frequency service that corrects continuous but small deviations in frequency. [18].
- **Contracts for Difference (CFD)**. 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 [19]. 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.

C. Battery Market and owners

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 [20]. Most planned capacity, around 80%, is being built in the south region. The reason behind this is the demographic distribution of the country since 27% of population lives in that region [20].

Table I 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 [21].

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.

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 I: Key players on current battery market [21].

	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

D. 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. In pink is the planned battery capacity [21].

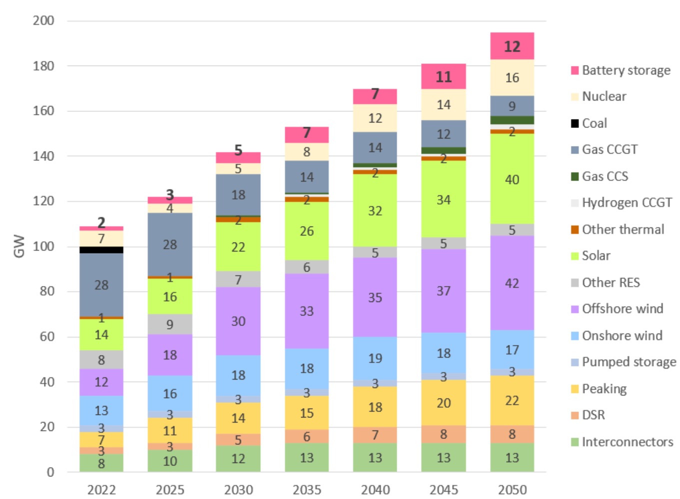

Figure 3: *UK installed capacity forecast from 2022 to 2050 [21]*

IV. REVENUE STREAMS ANALYSIS AND RESULTS

In order to build a profitable and successful project, an analysis of the different revenue streams is done.

A. Price Arbitrage

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 [3]. Figure 4 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.

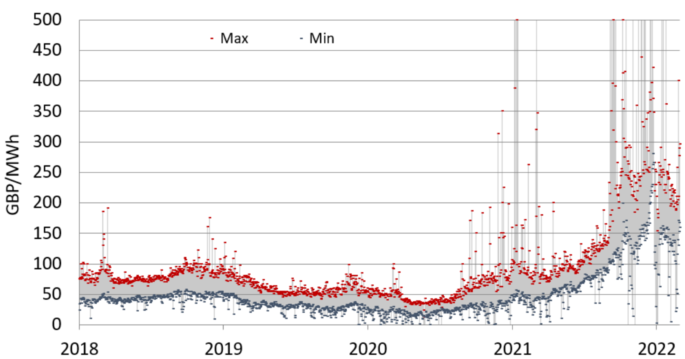

Figure 4: *EPEX Day-Ahead Power Prices in UK from Jan. 2018 to June. 2022*

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. 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 [22]. Standard Deviation is the square root of the sum of squared differences from the mean all divided by the amount of samples.

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

For this thesis, the volatility (standard deviation) is calculated for all years where we had raw data (2013-2022). 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 5, 6 and 7 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.

1. *Year 2020*

As can be seen in Figure 5, 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 II shows the values calculated for the analysis of this year.

Table II: 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%

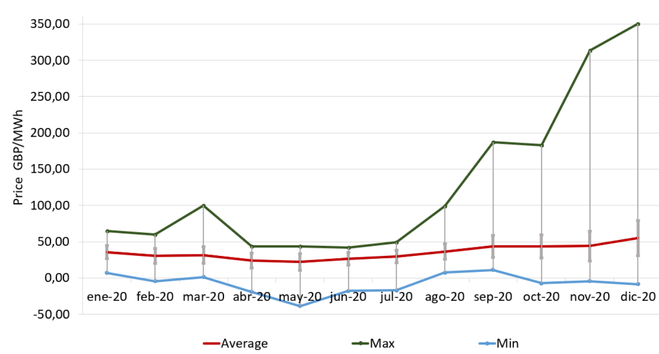

Figure 5: *Volatility values in 2020*

2. *Year 2021*

As can be seen in Figure 6, 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 III shows the values calculated for the analysis of this year.

Table III: 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%

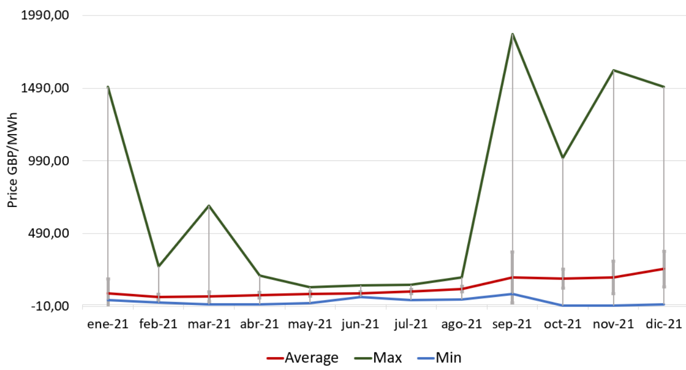

Figure 6: *Volatility values in 2021*

3. *Year 2022*

As can be seen in Figure 7, 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 IV 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 IV A 4.

Table IV: 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%

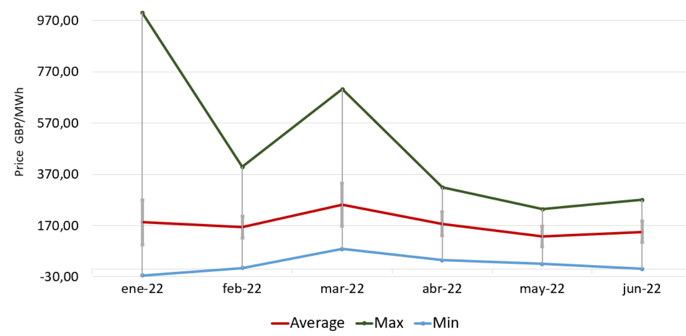

Figure 7: *Volatility values in 2022*

4. *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 8 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.

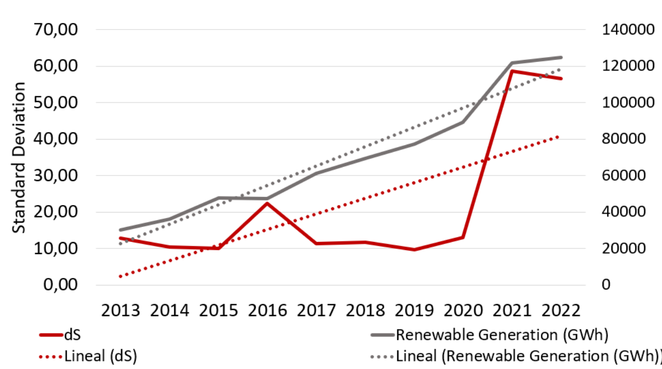

Figure 8: *Trend of standard deviation and renewable generation from 2013-2022 [23, 24]*

The same comparison is done in Figure 9 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.

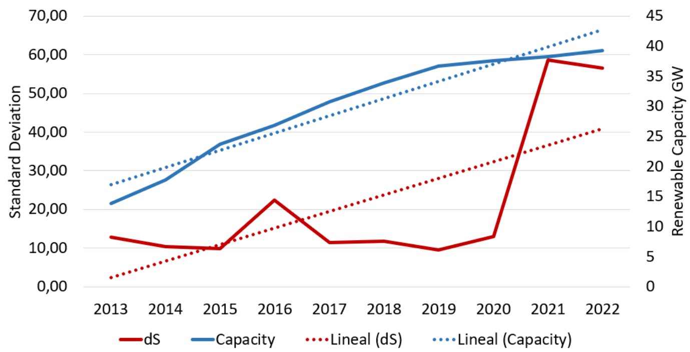

Figure 9: *Trend of standard deviation and renewable installed capacity from 2013-2022 [3, 23]*

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. 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. Figure 10 shows analysis of frequency distribution of electricity prices in UK based on data provided by Aurora Energy [21]. It shows how, over the years, the frequency of highest (green) and lowest prices (gray) keep increasing.

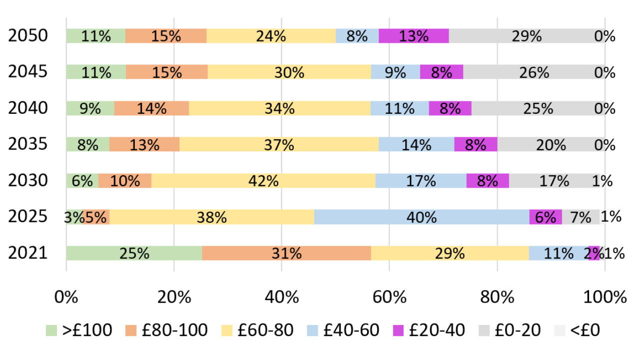

Figure 10: *Frequency distribution of the electricity price from 2021-25 [21]*

5. *Investment case*

In Section IV A 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 [21]. Table V shows the breakdown of costs for a large-scale Li-ion battery in 2022.

Table V: CAPEX breakdown costs Li-ion battery

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

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

Table VI: 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.

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 VII 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 V 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. If it is positive, government should implement new regulation so battery investors receive support to develop this technology.

Table VII: 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 11 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.

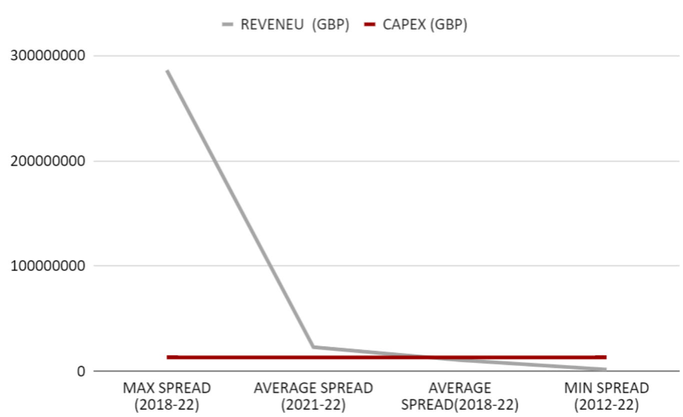

Figure 11: *Comparison of CAPEX and revenue value for each spread of the investment case.*

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, which is not the case for the whole lifetime of the battery. From Figure 11 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 average spread value for which the investment of a battery system would be profitable for any private owner.

B. 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 [4]. 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.

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 [21].

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

$$CMpaym. = [AuctionPrice]x[De - rate]x[Capacity] \quad (2)$$

Where, Annual CM payment is in £, Auction clearing price in £/MW, De-rating factor in % and 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 12 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.

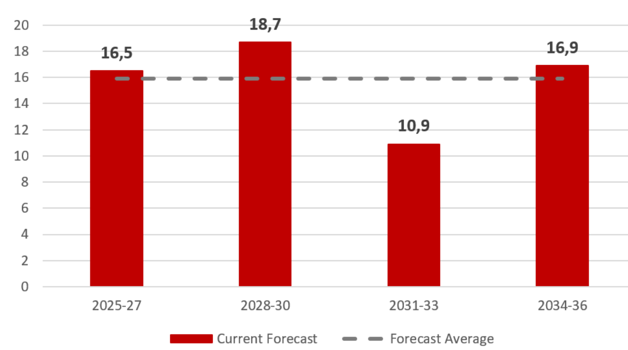

Figure 12: *Average CM forecast prices in £/kW [21].*

C. Ancillary Services

Ancillary services are in charge of maintaining the grid's 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.

1. 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 [4]. 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 [4].

V. SUCCESS CASE

A. 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 [25].

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. 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/MWh instead of jumping up the prices of around 12000 AUD/MWh. 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 [26].

VI. CONCLUSIONS AND FUTURE WORK

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. 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.

The results can lead to further analysis in the future. Some revenue streams seem more promising than others. 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.

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 constantly since technology and regulation evolve really fast and those changes could encourage companies to invest on batteries.

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