Understanding the Profitability Potential of Ancillary Service Markets: Techno-Economic Analysis of a Hybrid Power Plant

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Abstract

This thesis project's goal is to perform a techno-economic analysis of a hybrid power plant participating in three separate markets (wholesale electricity, firm frequency response, and capacity) in the United Kingdom, seeking to determine the optimal configuration of technologies and the plant's required market tender fee. To achieve this, multiple configurations of three main technologies (solar photovoltaic cells, batteries, and natural gas-fired generators) were analyzed using an energy system optimization tool. To make this possible, the software had to be modified by developing new scripts to increase its functionality, which would enable it to provide an optimal case for each of the four configurations under consideration. The main factors that were compared between each plant were their capital expenditure (CAPEX) value, the tender price required for providing frequency response services (FFR Fee), and carbon emissions. Results showed that a Battery-Generator plant with 20 MW of generators and 5 MWh of battery storage provided the optimal combination of CAPEX ($11.05 mil) and FFR Fee (63.22 $/hr), since the CAPEX was 34% lower than for a Battery-Generator plant consisting of 8 MW of generators and 20 MWh of battery storage, the FFR FEE was 23% lower than a photovoltaic-battery-generator plant, and the CAPEX was 71% lower than for a 32.5 MWh battery stand-alone plant. However, a sensitivity analysis based on predicted market trends found that other solutions could be superior and that choosing a configuration that can evolve with time would be wise.

Keywords: Techno-Economic Analysis, Energy Markets, Optimization, Battery Storage

1 Introduction

As the year 2020 draws closer, countries in Europe strengthen their push toward Horizon 2020 and a lower carbon future by investing in renewable energy production technologies. In certain countries, the electricity mix in the grid is starting to be taken over by electricity generated from renewable energy sources (i.e. solar power, wind power, and hydro power). In some cases, whole countries are running on 100% renewable energy for short periods of time, as was the case for 4 straight days in Portugal in 2016 [1]. All of this is positive news and means that things are heading in the right direction, but there are still some looming problems that need solving. One of the main issues that needs to be addressed moving forward pertains the intermittency of renewables. An unexpected cloud can pass overhead and constrict the production of a solar photovoltaic (PV) plant for several minutes. Similarly, a drastic variation in wind speed, in either direction, can reduce the output of a wind park or temporarily halt their production, full stop.

Due to the variability of electricity production sources feeding into a grid, fluctuations are expected. Small fluctuations are commonplace and do not require reactionary measures. Large fluctuations, however, are less frequent but far more detrimental to equipment performance and grid stability. A large variation in the frequency can cause instability in the rotational speed of a grid-connected turbine which leads to potentially damaging vibrations in the blades [2]. This issue has given rise to the requisite of having Firm Frequency Response (FFR) plants in place that are capable of rapidly coming online and generating electricity when the production from other sources drops off. In order to ensure that a system fault or blackout doesn't occur, these plants must respond to an event within 10 seconds of its occurrence [3].

Services like FFR do a great job of ensuring that current electricity generation is not in jeopardy, however in an effort to plan ahead and guarantee that their systems won't encounter any issues in the years to come, countries have begun to enact a new device known as a Capacity Market (CM). The general idea is that each country's grid transmission operator (TSO) reaches agreements with plants four years ahead of time to so that they can be certain that there will be enough future installed capacity to meet their demand projections. The United Kingdom launched its Capacity Market in 2014, and it is going to start paying plants for their generating capacity in the coming year (2018) [6].

From the perspective of energy project developers in the UK, the FFR and CM markets are just a few of many avenues to supplement the revenue generation of a newly built or yet to be constructed plant. Revenue supplementation, going above the simply generating and selling electricity to the grid, has become necessary so that the project developers and plant operators can ensure a project's profitability, and thus, it's viability. This need stems from the fact that over the past decade the U.K., along with many other developed countries around the globe, has seen a drop off in the overall energy and electricity demand led by the introduction of new, energy-efficient technologies along with higher industry standards for efficiency [4, 5].

Thus, in recent years, in an effort to combat the decrease in demand and the increase in competition, developers have started offering their generation services in a variety of ways (e.g. FFR tenders). This sets up the central idea of the work that was performed hereunder: under the current multi-market conditions present in the U.K., what type of hybrid plant (technology and capacity-wise) should a developer seek to build that will both satisfy technical requirements while being financially optimal?

The answer to this question was particularly interesting to one of the main project partners that assisted in the completion of this work. This partner being Lark Energy, a developer and maintainer of commercial and utility scale energy projects. As a means of helping to narrow the scope of the project, Lark provided a list of specifications based on their current capabilities and desired business strategy. Pairing that with the technical contraints of the three technologies under consideration (solar photovoltaic modules, electrochemical batteries, and natural gas-fired generators), new models could be constructed in the simulation environment that was central to this thesis. An in-depth description of this simulation tool and the models it utilizied is given in section 2.

2 Methodology

The main tool utilized during the commission of this work was the Dynamic Energy System Optimizer, or DYESOPT for short, which is a MATLAB based tool that was developed by researchers at the Royal Institute of Technology in Stockholm, Sweden. For it to properly complete its calculations DYESOPT needs to be provided with the following:

- technologies to be used (i.e. Solar PV, CSP or gas generators)
- location (which determines meteorological data and price data)
- preferred operational strategy (baseload or peak-hour coverage)
- economic parameters (such as the countries sales tax rate or capital interest rate)
- financing structure (e.g. single owner)

With all of this information DYESOPT can then run a simulation which will calculate the production of the plant for every hour of the year (or less, if specified), the losses incurred by the equipment or operating strategy, plus the capacity factor of each piece of technology utilized. After tabulating the results for one year's worth of operation, DYESOPT then takes this data and extrapolates it – accounting for degradation – to represent the entire production lifetime of the plant. With this, the yearly revenue and operating costs can be established and the determination can be made as to whether or not the plant will be financially viable over the course of its projected lifetime. In this sense, viability is achieved when a plant manages to, at the very least, earn enough income (revenue minus operating costs) to pay back the initial investment plus any interest that had been accrued.

Initially DYESOPT had functional solar PV and battery models, as well as a combined PV-BESS model, however it lacked a gas generator model and subsequently any combined models involving gas generators.Thus the models and case specific dispatch strategies needed to be created before any simulations could be run.

2.1 BESS-Gen Model

This configuration allows for the plant to provide both types of dynamic frequency response while not requiring the generators to be constantly running since the battery can provide energy during the generator startup phase. The generators are present in this configuration solely for the purpose of providing secondary frequency response services, once they ramp up to full-power they run continuously for 30 minutes and then shut off. However, they are not connected to the batteries with the intent of using them to charge the batteries. Instead, the batteries charge from the grid when the electricity price is at its daily minimum or during high frequency events (where the electricity consumed by the batteries is free because the plant is helping to provide a regulatory service).

The dispatch strategy developed for this hybrid plant is one of the central items that was created during the investigation and development of these thesis results. Before the dispatch strategy can be enacted it relies upon some data concerning the market conditions. Thus, after DYESOPT has performed the sizing of the batteries and generators, it carries out an assessment of the electricity market prices for each day of the year and assigns priority charging and discharging hour. The simulation then runs back through and ensure that no priority hour is overlapping with an hour in which the plant is going to be providing a conflicting frequency response service (no discharging of the batteries when the frequency is high or vice versa).

The dispatch strategy is then carried out in the TRNSYS portion of the simulation, so that it can track the dynamic changes in the batteries' SOC, along with how many times the batteries were unable to provide frequency response services. Fgure 1 provides a flow chart overview of the dispatch strategy. After some consideration, it was decided to have the plant offer frequency response 24 hours a day.

It can be seen that other than studying the grid frequency and the electricity price, the other major consideration that is made by the dispatch strategy is the SOC of the batteries. In some situations, the battery SOC is either at a minimum or maximum and the market conditions do not encourage charging or discharging, so when this occurs a "no action" command is given and the plant simply stands idle until market conditions change. Based on related literature regarding energy arbitrage through battery storage, it was decided to allow the simulation to investigate the effects of raising the minimum SOC above that of the battery's DOD. If they are providing frequency response services the batteries are allowed to reach their DOD level, otherwise they wouldn't be able to discharge below a pre-set percentage. Later on, the optimization would determine what the best minimum SOC for the batteries would be, in terms of economic performance and maximizing operational life.

Once the dynamic portion of the simulation has completed its iterative process, the model then moves on to tabulate the totals for the first year's operational production, usage and consumption. These values are fed into the thermo-economic calculation script, specifics of which will be addressed in section.

2.2 PV-BESS-Gen Model

The addition of photovoltaic modules to this configuration adds an extra layer of complexity to the simulation and the dispatch strategy, but the general structure stays the same. The batteries are still looking to charge and discharge at the cheapest and most expensive hours, respectively. The generators are still in place to provide the long-term reliability needed for secondary frequency response.

Before DYESOPT can enter into the dynamic portion of the simulation it is necessary for it to examine how the two chosen technologies (PV and batteries) interlink. Depending upon the specified capacities of the two and the chosen inverter type, it could be that there is going to be curtailment of the PV based upon the maximum charging rate of the BESS relative to the maximum output of the PV or based upon the maximum power rating of the inverter.

The main benefit that this configuration can provide is that the with the PV in place the batteries can use the solar production to charge and avoid paying for electricity coming from the grid. If the batteries are sitting idle at full charge capacity, any PV production can be directly sold to the electricity market.

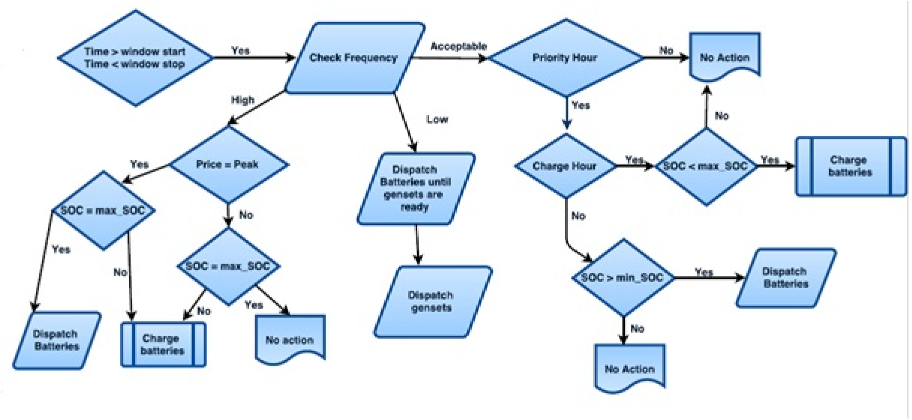

Figure 1: Flowchart which shows the decision making process implemented by the BESS/Gen model pursuant to carrying out the dispatch strategy

3 Economic Calculations

3.1 Plant Revenue Streams

Reviewing figure 2, with the knowledge that the capacity market has a pre-established price and that the model uses historical price data for the electricity market, it can be seen that these two values are fixed and thus the only ones that are malleable are the availability and nomination fees of the FFR services.

The availability fee ($/hr) is one which is paid to the FFR provider for each hour of their tendered contract. The nomination fee ($/hr) is awarded to the plant when they actuallly provide services related to a frequency event, so in theory it can be paid to the FFR provider for all or a fraction of the hours in their tendered contract. However, it was stated by National Grid that “Historically, for all tenders that have been accepted, all of the available windows have been nominated” [14]. In a review of all the accepted tender offers for the year 2016 (all made available on the website of UKET), it was discovered that no plant offering less than 50MW of FFR capacity was given the nomination fee, only the availability. Taking this small contradiction into account, it was decided that in the simulation the nomination fee would be offered to the plant, and that its value would be 50% of the value of the availability fee.

Table 1: Table displaying the different economic parameters that were used as inputs for the simulation (* indicates values that were specified by Lark Energy)

Parameter	Value
Real Debt Interest Rate	5% *
WACC	12% [9]
Sales Tax Rate	5% [10]
Cost of Equity	10% *
Cost of Debt	8% *
Share of Debt	70% *
Rate of Inflation	3% [11]
Plant Lifetime	25yrs *

The review of accepted tenders also revealed some useful data concerning the competition. In 2016, many tenders have been awarded to 20 MW plants and their nomination fees all fell within a range of 260-450 $/hr. This helped to provide a benchmark as well as a boundary condition for the simulation. To prove that the proposed plant could compete with current market condition, it needed to be able to operate for a tender fee of equal to or less than its competition.

3.2 Revenue Calculation

$$\begin{aligned} Rev = {} & E_{tot,yield} \cdot E_{price} + CM_{price} \cdot Cap_{plant} \\ & + FFR_{fee} \cdot (h + 0.5 \cdot h - 2 \cdot P) \end{aligned} \tag{1}$$

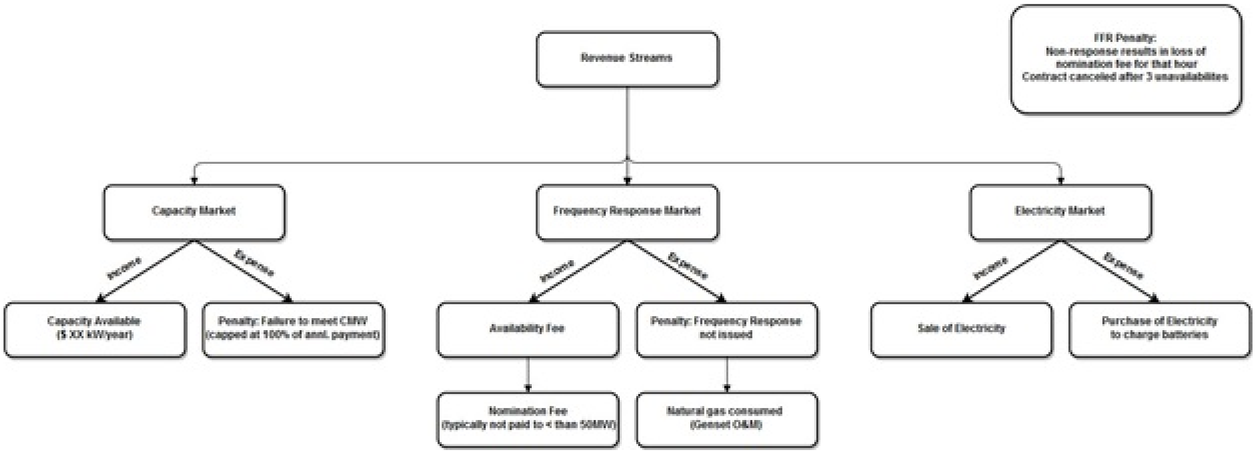

Figure 2: Figure portraying the three areas in which the power plant stands to earn revenue

$$FFR_{fee} = \frac{Rev - (E_{tot,yield} \cdot E_{price} + CM_{price} \cdot Cap_{plant})}{(h + 0.5 \cdot h - 2 \cdot P)} \tag{2}$$

In equation (1), $E_{tot,yield}$ is the total electricity yield (on an hourly basis) from the plant for year one, E_{price} is the electricity price for each hour of the year, the CM_{price} is the Capacity Market auction clearing price in (lb/kW/yr), Cap_{plant} is the installed plant capacity in kW, FFR_{fee} is the tendered price for providing frequency response services, h is the number of hours that the services are offered (availability fee), the $0.5 \cdot h$ term represents the nomination fee, and P is the number of non-response penalties that were incurred throughout the year (which is multiplied by a factor of two so that it nulifies the fee payment and assesses a penalty).

With the aim of finding the NPV at year 25 equal to zero, the required yearly revenue must be calculated. Once the revenue is known, equation (1) can be rearranged and becomes equation (2). Table 1 shows the chosen finanical parameters which were used in each simulation.

4 Results and Discussion

4.1 Genset Stand-alone Solution

One of the main issues with using the generators in a standalone capacity is the requisite of keeping them running 100% of the time in order to meet the fast response requirements of the FFR market. Keeping the generators running all the time increases the fuel consumption nearly 100-fold over the BESS-Gen case examined below, and because of this the required FFR tender price is driven up so that it can cover the increased operating costs of the plant.

Table 2: Performance metrics for the gas generator stand alone simulation

Indicator	Value	Unit
Capacity	20	MW
CAPEX	7.96	mil USD
OPEX	6.04	mil USD
FFR tender prices	421.91	USD/hr
CO_2	36580	tonnes
Operating Income	0.91	mil USD

Examining table 2, it can be seen that the genset standalone option offers an initial investment that is the lowest among all options considered, however the OPEX is nearly as large as the CAPEX (76%). A review of all of the accepted tender offers (made available on the National Grid website) for 2016 established that the average FFR nomination fee for 20 MW plants was approximately 340 $/hour [13]. So, although this option could still potentially compete with current FFR service providers, it is very vulnerable to the sensitivity of the natural gas mar-

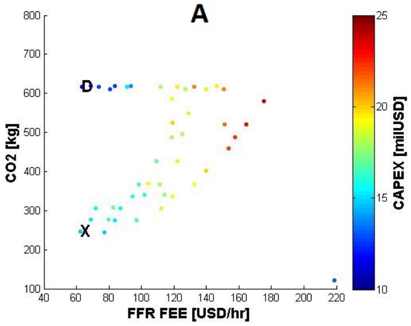

Figure 3: Results from the multi-variable optimization of the BESS-Gen power plant configuration which sought to minimize both FFR tender bid price and CO_2 emissions, data points representing the CAPEX values of each different configuration attempted during the optimization process. Point "D" represents BESS-Gen #1 and point "X" represents BESS-Gen #2

Table 3: Characteristics and financial metrics for the BESS-Gen plants (BESS-Gen #1) (BESS-Gen #2)

Indicator	BESS-Gen #1	BESS-Gen #2	Unit
Battery Capacity	5	20	MWh
Gen Capacity	20	8	MW
CAPEX	11.04	14.79	milUSD
OPEX	0.286	0.328	milUSD
FFR tender prices	63.21	62.26	$/hr
CO_2	616	246	tonnes
Operating Income	1.05	1.37	milUSD

ket, which only stands to increase in the coming years [12].

4.2 BESS-Gen Solution

For this configuration, a multi-variable optimization was performed to help isolate which combinations of battery and gas generator technology would prove to be the most economical and environmentally friendly. Surveying the graph (figure 3), each one of the points represents a different configuration of BESS-Gen power plant. Taking into consideration that the IRR was held constant, at a value equal to the WACC, it can then be understood that any one of these data points is equally as profitable as the next. It can be noticed that there are two points (indicated with the letter "D" and "X" sitting just to the right of each one, respectively) which achieved very similar values of FFR tender fee required for the plant, 62.26 and 63.21 $/hr, respectively. However, points D and X have rather different design characteristics, which are detailed further in table 3.

Even though a multi-objective optimization process was utilized in this simulation, the resulting graphs do not exhibit the typical pareto curve which might be expected. There are a few factors that could explain why this was the case. For one thing, certain guidelines for participation in the FFR market stipulate that if a service provider fails to provide balancing services more than three times in one month, the contract can potentially be terminated. In order to help the simulation isolate and eliminate plants which did not meet the FFR requirements, if a plant had any month(s) with more than three failed frequency responses, it would lose the FFR revenue for that month plus face an additional three month penalty (this additional penalty is not based on any information provided by National Grid, it is just a device that would help to eliminate bad plants from the simulation). The second factor that has distorted the shape of the data points on the graph is line of points at the top which all have 20 MW of installed gas generator capacity. Operationally these points are a bit different than the others with the reason being that as a whole, each plant is designed to offer 20 MW of electricity production and while also providing both primary and secondary frequency response services. If a plant has 20 MW of genset capacity, then it has no trouble to provide the full 20 MW for the entire 30 minutes required from secondary response providers, however, any plant with less than 20 MW of gensets needs the batteries to provide the additional production during this time, which sometimes is not possible if the battery system lacks the requisite charge.

From first glance it may appear that configuration BESS-Gen #1 is better suited for the needs of Lark Energy since it requires $3.75 million less in CAPEX and has slightly lower ($44,000/year) operating costs, yet this would assume that things like the price of natural gas or batteries stays the same. Pursuant to gaining a better understanding of how these plants could become more or

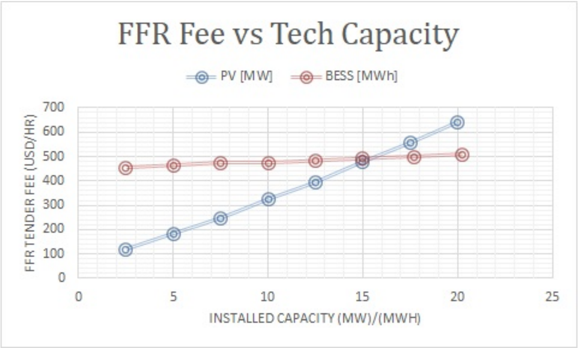

Figure 4: Graph illustrating how altering the PV capacity or the BESS capacity, while holding other capacities constant, can affect the required FFR tender fee

less favorable moving forward they will be analyzed in greater detail in section 4.5.

4.3 PV-BESS-Gen Solution

The PV modules were added into the configuration with the hopes of reducing the systems reliance on the natural gas-fired generators, to reduce the amount of electricity purchased from the grid to charge the batteries, and to increase the electricity that could be generated and sold. However, after the model was constructed and the simulations were carried out it became evident that this was not the case. In figure 4, the results of 16 different simulations are shown. In 8 of the simulations the installed PV capacity was varied while the values of BESS and gensets was held at 10 MWh and 15 MW, respectively, and then in the other 8 simulations the BESS capacity was changed while the PV and gensets were set at 15 MW each. The graph clearly indicates that a reduction in the PV capacity has a much larger impact on the necessary FFR tender fee than a reduction in battery capacity.

With regards to eliminating the need for gas generators, the PV doesn't pass the test, due to a lack of reliability in production. The best that could be achieved was reducing the genset capacity to 2 MW, which required 20 MW of installed PV and 20 MWh of BESS and the plant then needed a FFR tender fee of 620.36 $/hr. Thus, through optimization the most economical system was determined and its characteristics can be seen in table 4.

Table 4: Plant characteristics of the optimal PV-BESS-Gen configuration

Indicator	Value	Unit
PV Capacity	1.25	MW
Battery Capacity	2.5	MWh
Gen Capacity	19	MW
CAPEX	12.42	mil USD
OPEX	0.253	mil USD
FFR tender prices	81.72	USD/hr
CO_2	571	tonnes
Operating Income	1.24	mil USD

4.4 BESS Stand-alone Solution

The last configuration that was attempted was one that which only implemented batteries to perform energy arbitrage while also participating in the FFR and capacity markets. There was no need to perform an multi-objective optimization for this since there were not a vast amount of variables to alter. Considering the fact that the batteries in this configuration did not have the reliability of the generators to help shoulder the load of frequency response services, it was necessary to oversize the installed capacity of the batteries so that their participation in both markets would not be jeopardized. Figure 5 illustrates how additional battery capacity reduces the number of non-responses (Non-Resp) to low frequency events committed by the system.

As explained earlier, more than three non-responses in a month will result in a penalty and drive up the FFR tender fee that the plant must seek; in the graph the lowest three battery capacities (22.2, 25.2, and 27.8 MWh) all receive penalties for two months, the 30.4 MWh plant is penalized in one month, and the highest three battery capacities (32.9, 35.4, and 38 MWh) are reliable enough to where they do not incur any penalty. From the graph, the plant with the lowest required FFR tender fee was chosen as the best option, and additional information about this plant can be seen in table 5.

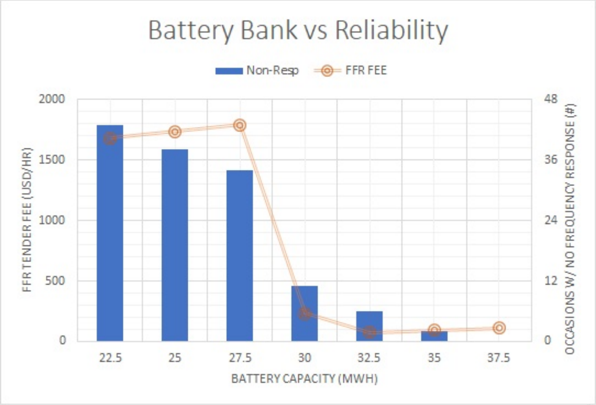

Figure 5: Graph portraying the relationship between installed battery capacity and the number of times the plant fails to provide FFR services, as well as the FFR tender fee the plant must charge

Indicator	Value	Unit
Battery Capacity	32.5	MWh
CAPEX	18.9	mil USD
OPEX	0.130	mil USD
FFR tender prices	76.50	USD/hr
CO_2	0	tonnes
Operating Income	2.01	mil USD

Table 5: Summary of the characteristics of the chosen BESS stand alone plant

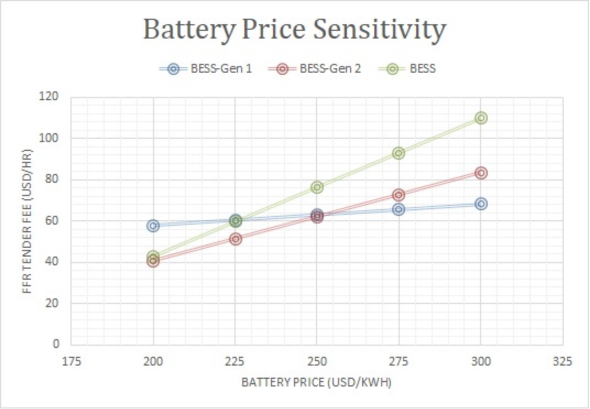

Figure 6: Sensitivity analysis to examine how changes in the market price of batteries would allow for changes in the FFR tender fee of each plant

4.5 Sensitivity

4.5.1 Battery Price Sensitivity

Examining figure 6 it can be seen that at the current price of 250 $/kWh the two BESS-Gen configurations are nearly identical in price, but as the price of batteries decreases configuration #2 becomes more attractive. Another observation is that the stand alone BESS configuration is the most sensitive to the battery price. A 10% reduction in battery price makes the BESS-SA equal to BESS-Gen #1, and with a 20% reduction in battery price it is able to pull even with BESS-Gen #2. The CAPEX of the BESS only option also becomes more competitive with the other two options as the battery costs are reduced; for a battery price of 200USD/kWh the CAPEX falls to $16.1 million, whereas the CAPEX of the BESS-Gen #2 reduced by a smaller margin to $13.1 million. In a report made by Bloomberg technology, they summarized the surveys for industry prices of Lithium-Ion batteries from 2013 to 2016 and showed that the prices have fallen from around 600 $/kWh to around 275 $/kWh [7]. For the industry prices to have dropped by over 50% in 4 years, it is reasonable to project them falling to 200 $/kWh or lower in the coming few years, meaning stand alone battery banks will become increasingly utilized.

Figure 7: Sensitivity analysis to examine how percentage variations in the electricity price (100% is present value) determine the FFR tender fee for each plant

4.5.2 Electricity Price Sensitivity

The sensitivity analysis for the electricity price (figure 7) was performed by adjusting the hourly electricity used in the simulation by a percentage multiplier. That is to say, 100% represents the actual electricity prices used in the model, any data points to the right represent an assumed overall increase in electricity prices and the data points to the left of 100% represent a decrease in prices. One trend that the analysis illustrates is the fact that the configurations which contain higher installed battery capacities are more sensitive to changes in the electricity prices. This trend is present because the more battery capacity a plant has the more it is able to provide electricity arbitrage to the market. Reviewing projections and future assumptions made by the UK government, it can be seen that they expect the wholesale electricity prices to grow in the coming years; estimating a 11% growth by 2020 and as much as a 39% growth over current prices by 2024 (see Appendix B.2) [8].

5 Conclusions

Looking back, the main objective for the work was to determine what type of hybrid plant (technology and capacity-wise) should a developer seek to build that will be able to participate in three electricity-centric markets (the wholesale electricity market, Firm Frequency Response services market, and the capacity market) while being financially optimal. This goal was accomplished through a multitude of steps, including a literature review, in depth understanding of the software that was to be used (DYESOPT and TRNSYS), and then the creation of two new hybrid plant models. Beyond the results themselves, these two models were probably the most important achievement that was made during the course of this thesis work. Their creation required countless of hours coding, debugging, several consultations of the online help database, postulating and validating theories, until finally the models were functional.

With these new models in place, simulations were performed to so that the valid combinations of the batteries, generators and PV modules could be discovered. At this point an optimization routine was run which highlighted a few superior configurations (two BESS-Gen plants and one BESS stand-alone plant) of the power plant and also specified the FFR tender price that this plant must obtain in order to meet its financial goals. The first potential solution (BESS-Gen #1) was composed of 20 MW of gas generators and 5 MWh of Li-Ion batteries, had a CAPEX of \$11.05 million and required a FFR tender bid of 63.22 \$/hr. The second viable solution (BESS-Gen #2) consisted of 8MW of gas generators and 20 MWh of Li-Ion batteries, its CAPEX was 34% higher than BESS-Gen #1 and it needed an FFR tender that was only 1.5% lower. Lastly, the final solution considered was a battery bank stand-alone plant with 32.5 MWh of installed capacity, its CAPEX was 71% higher and its required FFR tender was 21% higher. The reason that the latter two solutions were not overlooked in favor of BESS-Gen #1 was for the fact that parameters, such as electricity and gas price, stand to change in the coming years, thus changing the economic outlook of each solution. Finally, in order to further evaluate and quantify which potential plant type would offer the best selection moving forward a sensitivity analysis was performed based on these research predicted changes to market conditions. Research suggests that the in the years to come, the price of natural gas will increase, the price of Li-Ion batteries will decrease, and the price of electricity in the UK will increase. Under each one of these projections, the BESS-Gen #2 configuration improves in comparison with BESS-Gen #1. Also, in order for the BESS stand-alone system to outperform BESS-Gen #1, with regards to FFR tender fee, it would only require a 21% drop in the price of batteries or a 20% increase in the average hourly electricity price.

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