An Analysis of Solar Inverter Ratios, Battery Inverter Ratios, and their Effects on Capacity Factor and Economics of a DC-Coupled PV/BESS Site

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***Abstract*—The increase in Solar Generation deployment and the corresponding generation profiles they provide presents many opportunities for different deployment strategies and co-location with other technologies such as Battery Energy Storage Systems. A key design characteristic is the Solar Inverter Ratio, as well as the Battery Inverter Ratio for co-located sites. In this novel set of works, a sensitivity analysis is performed on the effects that changing the SIR and BIR can have on increasing the techno-economic performance of a solar installation where it is shown that up to an additional 0.92GWh of energy could be exported from a 5MW solar site by co-locating with a BESS and increasing the SIR. Following this, a first-of-its-kind study is undertaken into utilizing a DC-coupled BESS to provide frequency response services using the otherwise clipped energy from a high SIR site, showing the potential for significant economic improvements.**

***Index Terms*—co-location, dc coupling, pv, batteries, energy storage, inverter ratios**

I. Introduction

Solar Generation (SG, also often referred to as photovoltaic (PV) generation) is a continuously growing part of the electricity generation mix across the world, with the total share of electricity generated from solar worldwide rising from 1.78% in 2017 to 3.74% in 2022 [1] and in 2022 solar generation contributed 4.4% to the generation in Great Britain (GB) [2].

The main drawback of SG is that the generation occurs at set times throughout the day, with no generation occurring in hours of darkness. Whilst this gives the generation profile a predictable nature, it also means that the peak SG output does not align with the peak demand on the grid [3]. Many studies have been undertaken on a range of aspects of SG installations from Maximum Power Point Tracking (MPPT) [4] to load shifting and frequency response [5].

One approach utilized for maximizing the export of a given site is to oversize the solar panels in relation to the inverter [6]. The relationship between these two values is called the Solar Inverter Ratio (SIR). If the maximum generation capacity of the SG is equal to the inverter rating, then the SIR will be equal to 1. A SIR of 1.4 for a 5MW inverter would result in installing solar panels with a generation capability of 6MWp. The result of increasing the SIR is to increase the average power through the inverter as the solar panels will not produce peak power throughout the day and leave the inverter underutilized.

Battery Energy Storage Systems (BESSs) are well suited to be co-located with SG sites to support system balancing due to their good energy density and low cost [7] [8]. When co-locating BESSs with a SG site there are two main approaches available which consist of either AC or DC coupling. Simplified connection diagrams for the two approaches are shown in Fig. 1. The benefit of DC coupling when compared to AC coupling is that it reduces the overall cost of the power electronics by virtue of the BESS and PV array sharing the inverter. However, it does remove a degree of flexibility, as the BESS then has a limited ability to operate in different independent services whilst the PV is generating.

An example daily profile of a SG is shown in Figure 2, which also includes showing the effect that installing a BESS would have on the output of the site. It shows the inverter being underutilized with a SIR = 1 (red) where the solar panels do not achieve peak power due to reduced solar irradiance. The dashed blue line represents the output of the solar panels with a SIR $>$ 1 which shows the power output being clipped above the inverter's maximum power. The final scenario includes a BESS (yellow) that will be charged when the output of the solar panels is greater than the inverter maximum power and then discharged as the solar power output reduces as the irradiance decreases towards the end of the day. In this paper, the Battery Inverter Ratio (BIR) is utilized in the same way as the SIR where a BIR of 1 indicates a 5MWh 5MW BESS for a 5MW inverter rating.

The chosen SIR and BIR values have a significant impact on the Capacity Factor (CF) of the site. CF is commonly used in renewable generation studies as a method of determining the proportion of available energy that a site manages to generate. It is calculated using Equation 1, where E_{actual}

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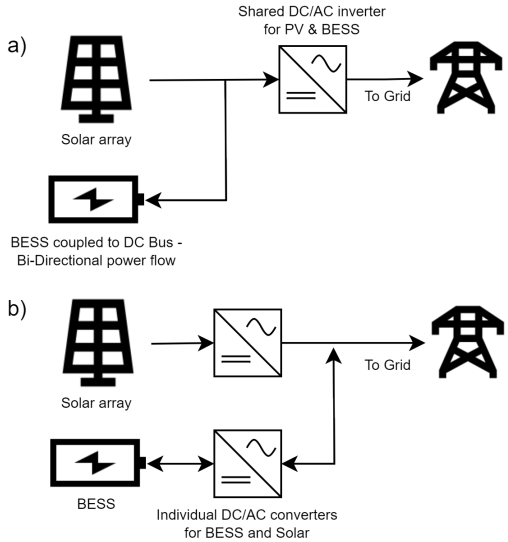

Fig. 1. Example topology of a Co-located BESS/PV installation a) DC-Coupled b) AC-Coupled

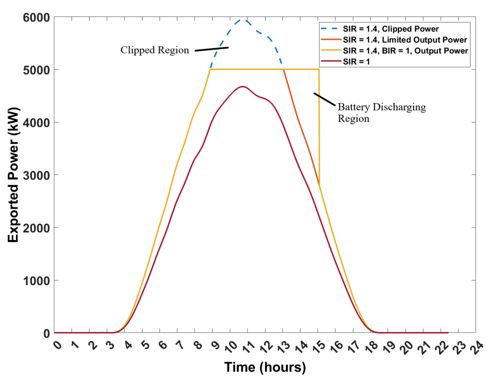

Fig. 2. Example simulation highlighting the effects of increasing SIRs and BIRs on PV generation

is the actual energy exported during the operational period ($t_{\text{Operational}}$), and P_{rated}, the rated peak power of the solar panels.

$$Capacity\ Factor = \frac{E_{actual}}{P_{Rated} \times t_{\text{Operational}}} \tag{1}$$

This paper presents a novel techno-economic study on SIRs, BIRs, and possible methods for further increasing the CF and economic returns of a PV installation. It also presents a novel introduction to utilizing the stored energy to provide frequency response services and the economic conditions that would be required for this to be viable.

II. Literature Review

The usage of BESSs for enhancing SG sites has been extensively studied across the literature [9] [10] [11]. However, the effects of varying SIRs and BIRs are something that is still an emerging topic.

The work in [12] provides an excellent overview of SIRs, detailing the most commonly utilized ratios which vary depending on the country that the SG site is being specified for. The SIR range presented in the work varies between 0.55-1.5 across the studies considered, illustrating that there is still uncertainty on the best approach when deciding on the most suitable SIR for an SG site.

An important study in [13] discusses the advantages of increasing SIR, with the increase to overall generation outweighing the loss of a proportion of peak hours generation to clipping. It also takes into account the degradation of the PV modules, showing that the impact of this is mitigated over time as the panels degrade.

The work in [14] also looks at optimizing the SIR for an installation based in Finland. It is important to note that the variability of irradiance has a significant impact on the operation of an SG site and therefore results from one region are not necessarily transferrable to other locations. In relation to this, the paper reports that the SIR obtained in this study is higher than that reported previously and notes this is likely due to geographical differences. The paper also highlights that increasing the SIR has a larger impact on smaller installations, due to the corresponding increase in proportion of cost for larger installations.

Several studies, such as [15] and [11] perform sensitivity analysis on the chosen SIR. In [11] a SIR of 1.85 is used and shows that 12% of energy across a year will be clipped by the inverter which highlights the potential for using a BESS to recover this energy using DC coupling that would otherwise be lost to clipping.

In terms of literature looking at varying BIRs, the work in [16] presents a study where the BIR of the site is varied between 0.25-1.00 for a SIR varying between 1.4-2.6. This study concludes that higher power capacity BESSs can enable the introduction of higher SIR rates from a technical perspective.

Additionally, the related works in [17] [18] [19] discuss various BIRs for implementation with different SIRs, varying from 0.25-1.0 across the studies presented. In [19] the work concludes that there may be benefits to replacing a lower BIR system (0.65) with a higher BIR system (1.0) once the BESS reaches the end of life, taking advantage of the solar degradation.

A. Novel Contribution

It is clear from the literature available that SIRs are a growing area of research and the further complication of including BIRs in this analysis is an area that is not commonly explored. The majority of the literature concentrates on clipping losses and optimization of the SIR for economic benefits. The novel work presented in this paper takes these studies as a foundation and provides further commentary on the use of DC coupling of a BESS to enhance an SG site.

III. Capacity Factor Enhancement

For this analysis, the inverter size has been set as 5MW, with the SIR and BIR then being varied to illustrate different

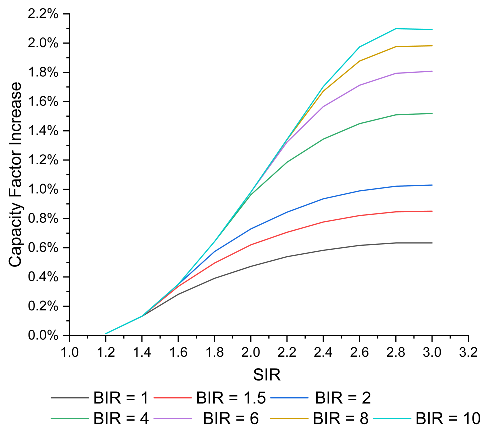

Fig. 3. Capacity Factor Increase for varying SIRs and BIRs

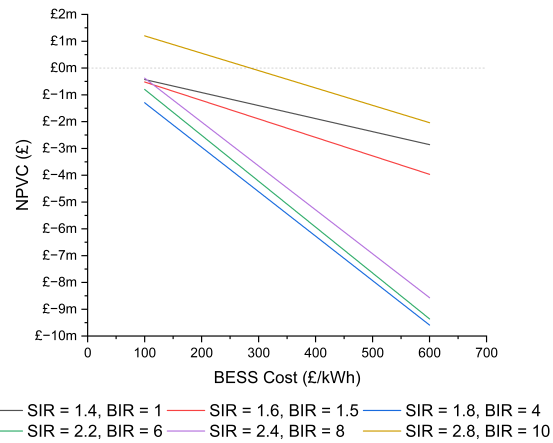

Fig. 4. NPVC for different scenarios for a range of BESS costs

approaches. Generation data has been taken from [20], and the system has been modeled using MATLAB/Simulink based on the model presented in [21]. The SG site is located in GB.

The Capacity Factor Increase (CFI) is a key metric to assess the technical viability of using a BESS for this application and uses the new CF with the BESS installed compared to the baseline CF with no BESS as calculated using Equation 1.

The results of the simulations are shown in Figure 3, which illustrates that the CFI increases level off significantly at higher SIR values. Additionally, at lower SIR values there is minimal benefit from increasing the BIR, with the impact of introducing a BESS becoming more prominent as the SIR increases.

The peak increase achieved is 2.09% which would represent an additional 0.92GWh of energy over the course of a year. This increase does occur at a more unrealistic SIR of 3.0, but for a more commonly used SIR of 1.4, the largest increase would still amount to an additional 0.57GWh of energy over a year. At the lowest SIR studied (SIR = 1.2), there is a minimal effect (<0.02% CFI) from introducing any size of BESS, suggesting this approach would be unsuitable for any SIR below this value.

The important question that arises from this study is how this translates to economic impact, and whether these values of CFI can result in BESSs being commercially viable for deployment in this application.

IV. Economic Analysis

The economic analysis is conducted using the strike price of the most recent Contracts for Difference (CfD) auction, with SG valued at £45.99/MWh [22]. Net Present Value (NPV), given in Equation 2, is used to calculate the base value of the site with no BESS installed. The new NPV with the BESS installed is then calculated and compared to the base NPV to produce a Net Present Value Change (NPVC) metric which is used to analyze whether the addition of a BESS would have a positive or negative economic impact.

$$NPV = \sum_{n-1}^{N} \frac{C_{revenue}}{(1+d)^n} - C_{investment} \tag{2}$$

Figure 4 shows the initial results of this set of simulations. A range of different combinations of SIR and BIR were chosen for analysis to provide an overview of the different economic impacts that the combinations result in. The cost of the BESS in £/kWh was then verified between £100/kWh and £600/kWh.

It is apparent that very few combinations of SIR and BIR result in a positive economic impact. The NPVC becomes positive for one combination of SIR and BIR, which only occurs at a BESS cost of £285/kW and below. This is lower than the commonly quoted value for BESS costs within the literature [23] and suggests that during current economic conditions, this approach would not be suitable.

In Figure 5 this is further explored with the SIR set as 2.8 and the BIR subsequently varied between 2 and 10. It is evident that decreasing the BIR results in further negative economic performance, although it should be noted that at a BIR of 8, there is still a positive economic impact at lower BESS cost levels.

This section suggests overall that whilst there can be a significant technical performance increase for an SG site, the economic case makes the deployment of BESSs non-viable. It is from this point that the following section explores an alternative method for increasing the economic viability of the site.

V. Provision of Frequency Response Services

A potential approach for increasing the economic impact of installing a BESS at an SG site is to utilize the BESS for providing other services, rather than simply for the export of generated energy. Whilst the previous section highlighted the advantages that different SIR and BIRs can have, the literature suggests that SIRs above 1.6 are unlikely to be utilized [12] despite being commonly studied for potential benefits [13].

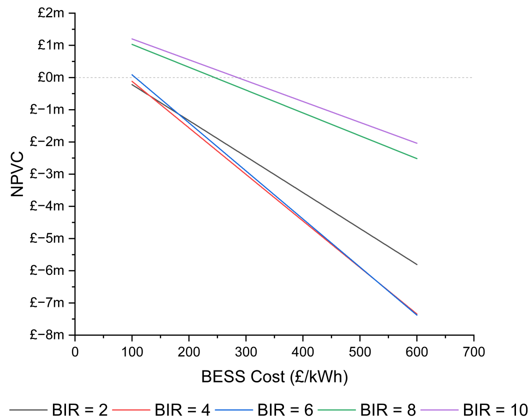

Fig. 5. NPVC for different BIRs when SIR = 2.8 for a range of BESS costs

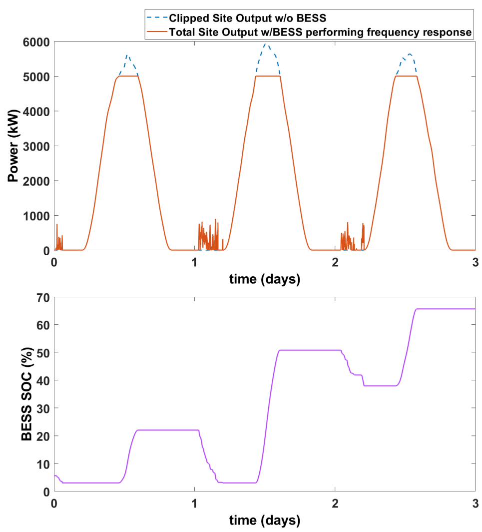

Fig. 6. Example site output showing clipped site output, total site output with a BESS performing DCL, and BESS SOC

Therefore, a novel new scenario is now proposed in order to increase the economic viability of a site with a SIR of 1.4 through the installation of a BESS. Under this scenario, the BESS still charges up during the periods of generation in excess of the inverter size as discussed in the previous section. However, instead of then discharging when the site output falls below the inverter limit, the energy is stored to be utilized for providing a frequency response service. An example site output for this approach is shown in Figure 6

Due to the topology chosen for this analysis being DC coupled, the BESS would be unable to provide services where charging events would be required, hence Dynamic Containment Low (DCL) has been chosen as the delivered service. The bidding for response services is split up into 6 Electricity Forward Agreement (EFA) blocks, and in this analysis, it is assumed that the BESS will only provide DCL in EFA block 1, which is between 11 pm and 3 am each day. For the purposes of this study. providing DCL in units <1MW is allowed due to the small size of SG and BIR ratios considered.

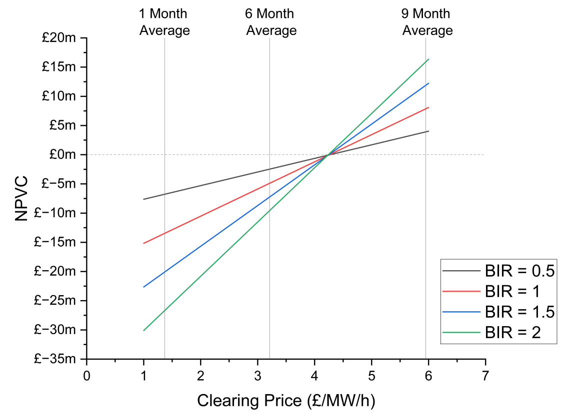

Fig. 7. NPVC for different BIRs when SIR = 1.4 for a range of DCL clearing prices showing the 1 month, 6 month and 9 month average clearing prices

DCL is a service offered by National Grid ESO that involves only discharging events [24]. It is therefore ideal for use in this scenario, where the BESS will be charged up during the day but then will subsequently discharge overnight whilst providing the DCL service.

For the simulations, the service being provided is set as equal to the BESS size being utilized at a 1:1 ratio. The Clearing Price (CP) (which is the price paid for providing the service in £/MW/hr) is varied between the current (as of June 2023) 1-month and 9-month average prices to illustrate the range of possible returns [25]. The NPVC for varying BIRs is then shown in Figure 7.

For the purposes of this study, providing DCL in units <1MW is allowed due to the small size of SG being simulated and the BIRs considered. The results show varying degrees of linear increases for the different BIRs, with the higher BIRs seeing steeper increases in NPV as the CP is increased. At the 1 and 6-month average values, the NPVC is significantly negative, however, if the clearing price were to rise towards the 9-month average and beyond then a significantly positive economic impact can be achieved.

The CP at which all 4 studied BIRs become economically viable is very similar, varying between £4.24 and £4.27. It is therefore reasonable to assume that for this approach to be viable, the CP would need to increase from the levels currently being experienced. However, the results do show significant positive NPVC can be achieved through co-locating a BESS with a SG site and offering overnight frequency response services (DCL).

VI. Conclusions and Future Work

Overall, this work has presented a novel investigation into the effects of BIR and SIR on the techno-economic performance of a SG site with a co-located BESS. The analysis showed that increases in CF gained by increasing SIR tend to level off at higher SIRs, providing minimal additional benefits. A similar pattern is observed when increasing the BIR of the site, with up to 2.09% CFI achievable.

This analysis was then followed with an economic assessment of the site to explore whether the high BIRs required for larger CFI increases were viable. This analysis showed that at low BESS costs (<£280/kWh) and when SIR = 2.8, a very high BIR (BIR = 10) could be economically viable, compared to the other combinations of BIR and SIR studied which did not provide a positive economic impact.

Finally, a first-of-its-kind study was conducted into increasing the economic performance of the site through the utilization of the DC-coupled BESS to provide a discharging-based frequency response service (DCL) during EFA block 1 (11 pm-3 am). The results of this analysis showed the clearing price that would be required in order for this approach to be successful, suggesting that when the previous 9-month average clearing price is considered, this approach would provide a positive economic impact.

This work highlights that a SG with co-located BESS can provide both generation and grid stability services whilst increasing the economic performance of the site. This could have a significant impact on the viability of SG in smaller electricity networks.

Future work should consider the degradation of the solar panels over the lifetime of the system and how this may affect techno-economic performance, as well as considering other opportunities within the existing GB market framework to provide additional ancillary services.

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