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# Techno-Economic Assessment of Grid-Level Battery Energy Storage Supporting Distributed Photovoltaic Power

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**ABSTRACT** Centralised, front-of-the-meter battery energy storage systems are an option to support and add flexibility to distribution networks with increasing distributed photovoltaic systems, which generate renewable energy locally and help decarbonise the power sector. However, the provision of specific services at distribution level remains under development for real applications in industry. To this end, this paper presents an exhaustive techno-economic analysis of the role of front-of-the-meter battery energy storage systems in primary distribution networks with presence of distributed PV covering: (i) the siting decision for storage systems using multi-objective genetic algorithm optimisation; (ii) the response when smart capabilities for PV inverters (e.g., volt-var control) are present; and (iii) the quantification of revenue streams and compensation schemes that would bring positive profitability when providing distribution-specific services based on the supply of real and reactive power. The performance of grid-level battery energy storage technology is evaluated in the IEEE 34-bus system particularised to the distribution code of Northern Ireland, UK. The techno-economic assessment covers one year of simulations at 1-minute resolution performed with the simulation tool EPRI OpenDSS and its Python communication interface. The results show that, besides the technical benefits of centralised battery storage systems, the economic compensation based on traditional transmission-level services is not sufficient for the profitability of these projects. Several ideas are explored to improve the profitability of these systems considering the local value and decarbonisation they add. The findings presented can direct system operators and regulators towards developing schemes to incentivise centralised battery energy storage projects in distribution networks in the context of distribution-level services.

**INDEX TERMS** Battery energy storage systems, distribution network services, distributed solar energy, flexibility services, photovoltaic power.

## I. INTRODUCTION

Solar photovoltaic (PV) technology has experienced the largest annual capacity additions since 2016 when compared to other major renewable energy technologies (i.e., hydro and wind) [1]. This growth in PV technology is visible in electric distribution networks, where PV systems have more presence than any other renewable distributed energy resource [2]. The integration of distributed PV systems in electric distribution networks has promoted a transition towards decarbonising power systems. However, there are certain technical challenges related to the variability and intermittency of solar energy that affect power output and its quality, and limit high-presence scenarios of distributed PV.

The variability and intermittency of solar PV systems can be mitigated with distributed storage systems, which permit a reduction of renewable energy curtailment and help operate stably low-inertia power systems, from microgrids

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to large systems, with high shares of non-synchronous variable renewable generation [3]. Among energy storage technologies, battery energy storage systems (BESS) are the storage technology with the highest applicability in electric distribution networks due to: (i) the time-scales required, from seconds to few hours; (ii) the range of power; and (iii) the range of energy capacity available [4]. BESS in distribution networks can be connected to the grid at a larger scale (centralised) or in smaller scale at the consumer level (decentralised).

Decentralised storage systems often refer to behind-the-meter solar PV systems coupled with battery storage systems at consumer level, where the value resides in increasing self-consumption to obtain a reduction in utility-bought energy, demand charges and the potential of a financial return from providing grid services [5]–[7]. Previous research studies in several geographical regions showed that the economic profitability of these systems highly depends on the availability of favourable incentives, tariffs and schemes [5], [6], [8], [9]. Nevertheless, the provision of grid services from small-scale prosumers is nowadays very limited due to the lack of supporting policy frameworks and the current operation of power markets conceived for larger generators in the MW range.

Utility or grid-scale energy storage refers to large storage units located in the low- (LV) or medium-voltage (MV) distribution network, typically downwards of a distribution transformer, serving to mitigate the constraints derived from distributed generation. Grid-scale energy storage can help stabilise the power networks by reacting to grid demand with a range of applications related to power quality, ancillary services or supply of energy in a centralised manner [4]. When compared to decentralised storage, centralised storage systems in the distribution network can represent a more cost-effective solution for the planning of the distribution system in the long-term [10]. In addition, these systems can minimise losses, thermal loading of power lines, voltage fluctuations, and increase the reliability for security of supply [11], [12]. Potentially, grid-scale systems have a more favourable position economically than smaller-range micro-generation systems due to the possibility to provide grid services and participate in electricity markets [13]. In these systems, the high cost of BESS drives the need for optimising the location and capacity (a.k.a. the siting and sizing problem of energy storage systems), and operation of the batteries [4].

To this end, the role of grid-scale energy storage systems in distribution networks to support distributed PV responds to multiple considerations. First, the siting and sizing decision, which affects its performance and it is subject to the characteristics of the network. As an optimisation problem, the siting and sizing problem has been proposed as a mathematical programming method (e.g., mixed integer linear programming problem [14]), as a heuristic method (e.g., genetic algorithms [11]) or other common methodologies such as analytical methods and exhaustive search [15]. These methods include multiple parameters and technical characteristics as input for these models to respond to the optimisation functions proposed. A review of the current literature indicates that studies on this topic focus mainly on optimising functions related to technical parameters of the network or storage system, at transmission or distribution level, and the economic considerations are often overlooked when addressing the sizing and siting of centralised BESS [4], [14]. A second consideration regards the applications or services that BESS can provide, which are typically classified into power or energy applications attending to the time span of application [16]. For example, in [14], the authors analysed the optimal location of BESS considering both primary and secondary distribution networks and concluded that BESS can reduce the total purchase cost of energy from the distribution substation.

The third consideration relates to the economic benefit from the grid services offered, and where substantial value and economic benefit that BESS can provide are not recognised by the current design standards in distribution systems [12]. Traditional services of generators are transmission-specific services (e.g., whole-sale of electricity, reserve or voltage/frequency regulation at transmission system level), where large-scale BESS could help deal with transient events at high renewable energy penetrations [17]. However, distributed generation, particularly PV, is mostly located at distribution network level. Therefore, storage systems deployed to mitigate potential technical issues caused locally by DG need to consider revenue streams from distribution-specific services, which reflect the local benefit and value that BESS offer technically. Yet, these services at distribution level are scarce. In the case of Northern Ireland (UK), distribution level services to provide real power flexibility are starting to be developed and tested in several trial zones, e.g., the FLEX project by the local distribution network operator (NIE Networks) whose trials start in October 2021 [18]. Studies looking at centralised BESS at distribution level have explored the provision of ancillary services for real power supply in MV systems considering power levelling [19], voltage control [20], and stacking of multiple ancillary services both in MV systems (e.g., frequency regulation and energy arbitrage) [21] and in LV networks (e.g., voltage regulation, energy arbitrage and peak shaving) [22]. Despite voltage regulation through reactive power supply is key in distribution networks, it is often omitted in the economic assessments of the literature. Overall, the majority of related previous studies have shown how, despite of the technical benefits, the economic viability of distributed BESS is marginal, limited or negative [19], [22], [23]. Yet, there are studies in the literature where the combined investment of BESS and distributed generation assets is positive (e.g., [14]), or where transmission-oriented services can bring a positive profitability to BESS (e.g., [21]) or marginal depending on the economic compensation (e.g., [24]). Nevertheless, a survey of the literature with a focus on centralised BESS illustrates a gap and urge for further development of distribution-oriented services provision.

**TABLE 1.** Taxonomy of relevant literature addressing the provision of flexibility services by battery energy storage systems.

| Network level | Voltage level | BESS services | Asset considered | Profitability | Study |
|---|---|---|---|---|---|
| Transmission | HV | Real power; ancillary | BESS | Negative/Marginal | [23] |
| Transmission | HV | Real power | BESS | Negative/Marginal | [24] |
| Distribution | MV | Real power; ancillary | BESS | Negative | [19] |
| Distribution | MV | Real and reactive power | BESS | N/A | [20] |
| Distribution | MV | Real power; ancillary | BESS | Positive | [21] |
| Distribution | MV and LV | Real power | BESS and DG | Positive | [14] |
| Distribution | LV | Real power | BESS | Negative | [22] |

Table 1 is a taxonomy table summarising relevant studies addressing the provision of BESS services in relation to the approach presented in this paper.

A fourth consideration is related to the distributed generation's technology to be integrated in the electricity network. When considering the integration of solar PV systems, a traditional approach for new grid assets (e.g., BESS, transformers or voltage regulators) based on hourly simulation steps is not sufficient. Solar radiation and, in consequence, PV power output, change at a second resolution due to diurnal variations of irradiance and cloud cover changes. Thus, PV integration studies would require higher temporal resolution (e.g., sub-minute resolution) to estimate the PV hosting capacity and the impact on the network. However, the availability of datasets with such resolution is scarce and the quasi-dynamic simulations of this type are computionally intensive. It is considered that simulations with time steps of 1-60 seconds are sufficient to capture the response of typical distribution equipment (e.g., voltage regulators or on-load transformer's tap changers) [25]. Yet, advanced analysis of PV hosting capacities should not be limited to assessment in high variable days, but to full-year simulations better understanding the impact and response of utility equipment [25], [26]. When considering PV integration in the planning of distribution networks, the assessment of reliability and risk analysis can also support micro-grids islanding behaviour, which is worth noting despite not being within the scope of this study.

Concurrently, the developments in PV inverter technologies have largely evolved and new control algorithms are increasingly implemented. Smart PV inverter controls (e.g., constant power factor, Volt-Var, or Volt-Watt) have been investigated to enable further PV hosting capacities. Single-phase PV inverters were shown to improve the voltage profiles of LV distribution networks through the use of reactive power control [27]. Similarly, [28] analysed the effect of smart inverter control algorithms and decentralised behind-the-meter BESS in PV hosting capacity and showed how BESS can further enhance PV penetration when combined with these methods. To that end, the effect that smart inverters deployment can have in grid assets, such as centralised BESS, should be investigated when considering PV integration.

The paper presents a multi-level analysis for the integration of a centralised BESS in an active distribution network with high distributed PV generation. The scope of this paper converges the considerations mentioned above with a focus on the provision of distribution-specific services by BESS that enable flexibility and add value locally. To that end, the assessment presented covers several aspects of grid-scale BESS and PV integration that are not commonly combined together in the literature, and where its methodological contribution lies. A first level of the assessment includes the optimal allocation of the centralised BESS attending to technical and economic parameters. The assessment then moves into the role of centralised BESS in the network by looking at: (i) its effect in the maximum PV hosting capacity; (ii) its role when smart PV inverters using Volt-Var control are present in the distribution network; (iii) its provision of flexibility through real and reactive power supply; and (iv) its equivalent economic revenue as part of energy markets. The specific contributions of this study are:

- A siting optimisation method for centralised BESS based on a no-preference optimisation approach using genetic algorithm, which considers a global optimal solution estimated from technical and economic parameters.
- The evaluation of performance for the centralised BESS response regarding maximum PV hosting capacity, real and reactive power supply and impact of network infrastructure, namely, in-line voltage regulators. This includes the performance over multiple PV penetration levels and different PV inverter technologies.
- The estimation of compensation schemes for the centralised BESS that would return a positive profitability following a break-even estimation method.
- The exploration of several concepts for the retribution of centralised BESS that could enhance and boost their profitability providing distributed-specific services in distribution networks.

The paper is organised as follows: Section II continues with the description of the methodology used for the paper, including the mathematical formulation, electric network definition and data sources. In Section III, the siting problem of storage systems is solved to determine the optimal location of grid-level BESS in the studied distribution network. Sections IV and V then present the technical and economic performance of grid-level storage, respectively, with the centralised BESS in the estimated global optimal location. Section VI continues with a sensitivity analysis for the economic profitability of the battery storage project. Section VII discusses the findings based on the results. Finally, Section VIII presents the conclusions and considerations for future work.

## II. METHODOLOGY

This section presents the methodological aspects permitting the techno-economic assessment of distributed PV and grid-scale BESS, including the mathematical modelling, the elements and characteristics of the simulated power network, and the cases and scenarios considered in the simulations. Fig. 1 presents a diagram with an overview of the methodology used in this study. A first step corresponds to the allocation of the centralised BESS following a no-preference optimisation approach using genetic algorithm, which estimates a global optimal bus from technical and economic inputs. Then with the BESS solution at the global optimal bus, the technical (step 2) and economic performance (step 3) are assessed. The methodology also considers a sensitivity analysis (step 4) using a parametric approach to evaluate the changes in the economic profitability of the centralised BESS attending to variations in macro-economic variables and the size of the energy storage system.

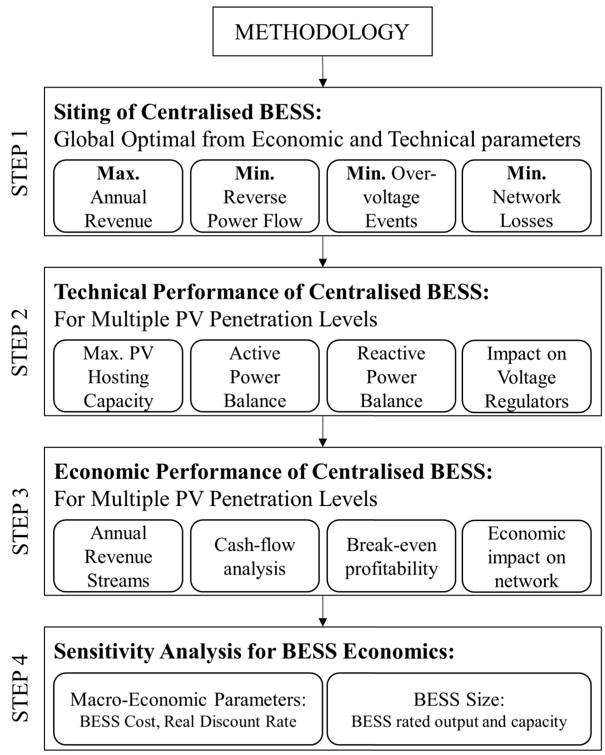



**FIGURE 1. Overview of the methodology used in the assessment of the centralised BESS, which consisted of 4 steps: 1) the siting decision of the storage system to find a global optimal bus attending to techo-economic parameters; 2) the technical performance of the BESS in the network; 3) the economic performance based on the technical solution; and 4) a sensitivy analysis to capture variations of the proposed characteristics of the BESS.**

This section presents the problem definition in Section II-A, which includes the definition of the objective function for the optimisation algorithm addressing the allocation of the centralised BESS, and it also includes the optimisation constraints and control algorithms implemented in the simulations. The test system is then described in Section II-B. The evaluated cases and scenarios are presented in Section II-C, and Section II-D presents economic-related considerations for the assessment of BESS in the network.

### A. PROBLEM DEFINITION

The problem definition addressed for the allocation of the centralised BESS in the distribution network is presented in this section. The defition of the problem includes the objective function sought, voltage and loading contraints in the network, the control of the distributed PV, and the dispatch algorithms of the centralised BESS.

#### 1) OBJECTIVE FUNCTION

The goal is to optimally locate the grid-level BESS within the distribution network with high penetration of distributed PV generation. The optimum location is determined by considering as a decision variable the bus within the network and the aim is a global optimal solution, which includes technical and economic parameters. The multi-parametric optimisation function follows a no-preference model based on genetic algorithm and it is given by the objective function shown in Eq. (1):

$$\min_{s.t. x \in B} \{a_1 \cdot R_x - [a_2 \cdot L_x + a_3 \cdot V_x + a_4 \cdot C_x] - Z \tag{1}$$

where $x$ is the bus belonging to the set of feasible buses $B$ in which the storage system can be installed (see Fig. 4) and the terms of the equation correspond to the normalised score of each of the multiple variables considered to obtain the global optimal bus for the grid-scale battery system, which are:

1) The total economic revenue from real and reactive power supply by the grid-scale BESS ($R_x$) in a specific bus $x$, which is intended to be maximised.
2) The electricity losses in the network ($L_x$) with the BESS in a specific bus $x$, which are aimed to be minimised.
3) The annual number of voltage violations ($V_x$), including under- and over-voltage events, if any, and which are minimised.
4) The annual energy fed back reaching the substation in bus 800 through reverse power flows or energy curtailed ($C_x$) if reverse power flows to the substation were to be avoided. This annual energy value is also to be minimised.

The term $Z$ corresponds to the ideal normalised values, unity. No-preference models are a type of non-linear methods working with multiple objective functions, where each objective function is considered equally important [29] and there are not initially defined optimal solutions, opposite to Pareto-based optimisation models. Our selected no-preference optimisation model is based on genetic algorithm (GA), which are inspired by the principles of natural selection and genetics. GAs use random choice to guide a highly heuristic search and can find global optimal solutions. In the proposed GA model, the optimisation routine initialises by randomly selecting the site among the permissible nodes and assigning a fitness score to each solution. The search procedure continues until the total cost reaches the lowest possible value guaranteed by the algorithm, which is controlled in Python programming. GAs have been proposed in the literature to analyse the siting and sizing decision of energy storage systems, e.g., [11], [30]. The coefficients $a_1$ to $a_4$ in Eq. (1), which are weighting factors, were set to unity in order to consider each variable of the global optimal objective function equally. The approach to the ESS siting solution through a no-preference optimisation model permits the use of multiple different variables, since these are normalised as part of the model. The normalisation method min-max or 0 to 1 normalisation, which is defined generically by Eq. (2), is used for the variables to find the most suitable bus as a solution.

$$z_i = \frac{x_i - \min(x)}{\max(x) - \min(x)} \tag{2}$$

The simulations of the test network to find the bus satisfying a global optimal location are performed for each of the cases with grid-scale storage (i.e. 'PV PF + BESS' and 'PV VV + BESS') and a PV penetration of 40%, which corresponds to the median PV penetration level in the range assessed. These cases and the range of PV penetration levels analysed are introduced in Section II-C. After defining the global optimal location for the grid-scale BESS, the techno-economic assessment is then performed for the whole range of PV penetrations levels.

### 2) VOLTAGE PROFILE CONTROL AT PV GENERATION POINTS

The simulations consider two control strategies for the supply of reactive power from the PV inverters, each of them presented in a different case. The control strategies are: (i) specified fixed or constant power factor; and (ii) Volt-Var control. Both control strategies are common in commercially available smart PV inverters [28], [31]. Through the variation of the reactive power output, the PV inverters can help regulate locally the voltage profile and mitigate the sudden voltage variations derived from the PV generation.

The specified or **constant power factor mode** permits the inverters provide a reactive power corresponding to the defined power factor (PF). Distributed generators are required to have a power factor between 0.95 inductive to 0.95 capacitive in the Northern Irish distribution code [32]. In this regards, the simulation uses power factor unity for the case with PV and grid-scale BESS. However, the hosting capacity is also tested with both power factor limits in the distribution code for the case without grid-scale BESS. Therefore, for the case of PV systems using a constant PF model, the reactive power output of each PV system $pv$ at a given time-point $t$ is given by the apparent energy (equal to the real power) and the angle between voltage and current $\phi$ as shown by Eq. (3).

$$Q_{t,pv} = S_{t,pv} \cdot sin(\phi) \tag{3}$$

The **Volt-Var mode** in smart solar inverters permits adjusting the reactive power output according to the grid voltage, so that the inverter contributes to mitigating voltage fluctuations and help avoid potential under- and over-voltage events. In this mode, real power could be curtailed to facilitate dispatch of reactive energy. Volt-Var control belongs to the category of smart-control for PV inverters and can benefit the network characteristics and extend the hosting capacity (HC) [28]. The Volt-Var control is defined mathematically by Eq. (4).

$$Q_{t,pv} = f(\%V_{t,pv}) \tag{4}$$

where the reactive power output given by the Volt-Var control is estimated as function of the percentage of nominal voltage ($\%V_{t,pv}$) for each inverter's point of interconnection at a time step $t$, which are presented in Table 2. These settings are defined according to the operational range of commercially available smart inverters and where the values V1 to V4 and Q1 to Q4 correspond to those illustrated in Fig. 2.

**TABLE 2.** Characteristics of the Volt-Var Control operation for the smart PV inverters. Source: SMA [31].

| | Q1 | Q2 | Q3 | Q4 |
|---|---|---|---|---|
| Reactive Power (% Pnom) | 50.0% | 0.0% | 0.0% | -50.0% |
| | **V1** | **V2** | **V3** | **V4** |
| Inv. Terminal Voltage (% Vnom) | 92.5% | 97.0% | 103.0% | 107.5% |

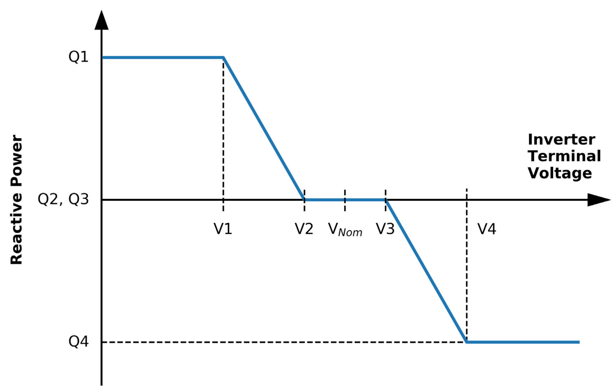



**FIGURE 2.** Reference points for the Volt-Var control of smart inverters. Reproduced from [31].

### 3) BESS ACTIVE AND REACTIVE POWER OPERATION

The centralised, grid-scale BESS is presented with independent control of its dispatch of real and reactive power. The real power control responds to the power flow reaching the bus where installed. When the centralised BESS operates as a load (charging), its behaviour can be defined as per Eq. 5:

$$P^{ch}_{t,eff} = P_{t,in} - P^{ch}_{t,losstot} \tag{5}$$

where $P^{ch}_{t,eff}$ is the effective charging power for a given time step $t$ that results from the actual input power $P_{t,in}$ subtracting the total charging losses $P^{ch}_{t,losstot}$. The total losses for the charging state are given by Eq. (6) and depend on the efficiency of the inverter $\eta_{inv}$ and the iddle state losses $P_{idl}$.

$$P^{ch}_{t,losstot} = P_{t,in} \cdot \eta_{inv} + P_{idl} \tag{6}$$

**TABLE 3. Characteristics of the grid-scale BESS.**

| Variable / Parameter | Value |
|---|---|
| Initial energy level stored | 66% |
| Depth of discharge | 20% |
| Inverter Efficiency Curve | $\eta_{inv}$ = (0.86, 0.9, 0.93, 0.97) |
| Inverter Per Unit Output | (0.1, 0.2, 0.4, 1.0) |
| Battery Inverter Power Output | 950 kW (50% of peak demand) |
| Energy Capacity | 3,800 kWh (4 hours) |
| Battery Inverter Capacity | 1,190 kVA (125% Rated Power) |
| Battery discharge strategy | Peak-shaving (threshold 1,110 kW) |
| Battery charge strategy | Low Peak-shaving (threshold 630 kW) |
| Reactive Power Operation | Volt-Var control mode |

The inverter's efficiency is considered to followed a linear relationship as function of of the inverter per unit output. The details of the relationship are available in Table 3, which also includes a summary of the characteristics considered for the grid-scale BESS. The energy stored in the BESS available for the next simulation time step $t + \Delta t$ is given by:

$$E(t + \Delta t) = E_t + P^{ch}_{t,eff} \cdot \Delta t \tag{7}$$

Similarly, when the centralised BESS operates as a generator (discharging), its behaviour in terms of power output can be defined by Eq. (8).

$$P^{dch}_{t,eff} = P_{t,out} + P^{dch}_{t,losstot} \tag{8}$$

where $P^{dch}_{t,eff}$ is the effective discharge/output power considering losses, $P^{dch}_{t,losstot}$ are the total losses in discharge mode that include the iddle losses and the inverter's conversion efficiency. Similarly to Eq. (7), the energy balance available for the battery in the next simulation step when discharging can then be given by Eq. (9):

$$E(t + \Delta t) = E_t - P^{dch}_{t,eff} \cdot \Delta t \tag{9}$$

One of the aims of the grid-level BESS is to limit reverse power flows within its capacity by using a low-level threshold of power below which the battery will charge, i.e. low peak-shaving. Another aim is to limit the maximum demand by performing peak-shaving services. The thresholds used for the peak-shaving and low peak-shaving were set to the 25$^{th}$ and 75$^{th}$ percentiles of the demand in weekdays for each of the seasons rounded to the nearest 10.

The reactive power dispatch of the front-of-the-meter BESS aims to assist with local voltage control through reactive power injection and absorption. To that end, Volt-Var control is considered for the reactive power dispatch, which is defined by Eq. (4), and where the operation set-points of the Volt-Var control for the centralised BESS are shown in Table 4.

The implementation of these control strategies is embedded within the tool used for the simulation (i.e., OpenDSS tool). The real power control is implemented with the element 'StorageController' defining the charging strategy as 'low-peak shaving' and the discharge as 'peak shaving', whereas the reactive power control follows a Volt-Var strategy and it is implemented with the element 'InvControl'. The maximum available reactive power output corresponds to the equivalent kvar remaining from the capacity of the inverter in kVA subtracting the real power output in a given instant. The technical characteristics of the grid-scale BESS are defined in Table 3, where the selected inverter's power output was 950 kW (50% of the peak demand) and the energy to power ratio is 4, which is typical in utility-scale storage projects [33]. Therefore, the techno-economic assessment for the BESS relates to its location, whereas its size is based on these empiric reference values from the literature. Besides these selected power and energy rating, 120 alternative variations of grid-scale BESS sizes are evaluated in Section VI.

**TABLE 4. Characteristics of the Volt-Var control operation for the grid-scale BESS inverter.**

| | **Q1** | **Q2** | **Q3** | **Q4** |
|---|---|---|---|---|
| Reactive Power (% Pnom) | 100% | 100% | -100% | -100% |
| | **V1** | **V2** | **V3** | **V4** |
| Inv. Terminal Voltage (% Vnom) | 50% | 95% | 105% | 150% |

#### 4) CONSTRAINTS

The optimization problem presented is subjected to a number of equality and inequality constraints for the network operation and the centralised BESS.

##### *a: NETWORK CONSTRAINTS*

There are several constraints considered in the electricity network, such as the power balance, voltage levels in the buses of the network and capacity loading in its lines. The total active and reactive power at any simulation time step between the substation, distributed PV and centralised BESS needs to be balanced with the total demand and network electric losses.

$$P^{gr}_t + \sum_{i=1}^{pv} P^{PV}_{t,i} \pm P^{BESS}_t = P^{Demand}_t + P^{losses}_t \tag{10}$$

$$Q^{gr}_t + \sum_{i=1}^{pv} Q^{PV}_{t,i} \pm Q^{BESS}_t = Q^{Demand}_t + Q^{losses}_t \tag{11}$$

where $P^{gr}_t$ is the power supplied by the grid at the time $t$, $P^{PV}_{t,i}$ is the power from the distributed PV systems, $P^{BESS}_t$ is the BESS power, $P^{Demand}_t$ is the electric demand, and $P^{losses}_t$ are the network lossess. Similarly, the subscripts and superscripts define the balance of reactive power in the network.

The voltage levels within the network are limited to the threshold 0.85 p.u. to 1.1 p.u. of the nominal voltage, which correspond to the thresholds for under- and over-voltage events (distribution code §7.11) [32], [34]. Mathematically, the voltage constraint in the network buses is defined by Eq. (12).

$$0.85V_N < V_{t,x} < 1.1V_N, \quad \text{for each bus } x = 1, \ldots, 34 \tag{12}$$

where $V_N$ is the nominal voltage of the network and $V_{t,x}$ is the actual voltage estimated in each bus $x$ for a timestep $t$ in the simulation.

Regarding the loading of the power lines, the capacity of the lines cannot exceeded its nominal current values ($A_{l,N}$). The loading capacity is given by Eq. (13), where $A_{t,l}$ is the current in a line $l$ at a timestep $t$ in the simulation.

$$A_{t,l} \leq A_{l,N}, \quad \text{for each line } l \tag{13}$$

### b: BESS CONSTRAINTS

The centralised battery system is also subject to a number of constraints. A first constraint is on the BESS power rating, where charged power ($P^{ch}_{t,eff}$) or discharged power ($P^{dch}_{t,eff}$) at any time step cannot exceed the predefined rating.

$$P^{BESS}_{t,eff} \leq P^{max}; P^{max} \in P^{ch}_{t,eff}, P^{dch}_{t,eff} \tag{14}$$

The maximum power input or output of the battery is also constraint by the maximum inverter apparent power output ($S^{BESS}_{t,max}$) when considering the effective real ($P^{BESS}_{t,eff}$) and reactive power ($Q^{BESS}_{t,eff}$) at any time step $t$.

$$S^{BESS}_{t,max} \geq P^{BESS}_{t,eff} + Q^{BESS}_{t,eff} \tag{15}$$

The grid-scale BESS will respond to the signals from to implement peak-shaving and low peak-shaving provided that its state of charge (SOC) is within the considered operation limits. These are given by Eq. (16):

$$SOC^{min}_t \leqslant SOC_t \leqslant SOC^{max}_t \tag{16}$$

The minimum state of charge at a given time step ($SOC^{min}_t$) is set to 20%, and the maximum state of charge ($SOC^{max}_t$) is 100%. Finally, the battery's SOC available for the next simulation timestep is derived from its previous step, as follows:

$$SOC_t = SOC_{t-1} + P_t \cdot \Delta t / E_t \tag{17}$$

## B. NETWORK DEFINITION

The assessment in this paper is performed in a distribution network system, since it is where distributed PV is generally connected [2]. The distribution network used in the analysis is the IEEE 34-bus test feeder, which is an actual feeder located in Arizona (USA). It has a nominal voltage of 24.9 kV and it is characterised by lightly-loaded, long lines. It presents two in-line voltage regulators, an in-line transformer for a short 4.16 kV section, unbalanced loading, and shunt capacitors. The feeder has both spot (connected in the buses) and distributed loads (uniformly in the line section) [35]. The full characteristics of the feeder are available in [36] and [37]. In the simulation, several characteristics of the feeder have been adapted to the distribution of Northern Ireland. The base frequency is 50 Hz and the infeed transformer, which does not have voltage regulation through on-load tap changing, is set with a supply voltage of 1 p.u. The statutory voltage limits are also particularised for the distribution code of Northern Ireland, that is: normal operation are between 0.94 p.u. and 1.06 p.u. (distribution code §13.3.1), and emergency operation between 0.85 p.u. and 1.1 p.u., which are also the thresholds for under- and over-voltage events (distribution code §7.11) [32], [34].

The IEEE 34-bus test feeder is originally defined with static loads in a single power flow analysis. For its use in a dynamic simulation, it requires a load profile to multiply the values of the loads in the feeder. In order to perform dynamic time-series analysis, the load profiles defined by Elexon's profile class 1 - domestic unrestricted customers [38] were selected. It is a typical UK normalised aggregated profile for residential consumers widely used in the literature. These profiles offer half-hourly data classified per season of the year (i.e. winter, spring, summer, high summer, and autumn) and day of the week (weekday, Saturday and Sunday). For the purpose of the simulation, the profiles were linearly upsampled to 1-minute resolution for a period of 1 year. The annual timeseries at 1-minute resolution with the per-unit profiles used for the electric load and the PV systems are available as a supplementary material of this paper.

The network was simulated using the Open Source Distribution System Simulator OpenDSS [39], which is a tool developed by the Electric Power Research Institute (EPRI), and its Python API for processing the results. When simulated with its defined loads and the designated average normalised demand profiles, the feeder has a peak load of 1.93 MW and an annual consumption of 8.28 GWh (including losses). The total system load in the base case (i.e., without PV) as observed by the substation is illustrated in Fig. 3 for the weekdays of each meteorological season, where the minimum annual demand is 433 kW and the percentiles are: 629 kW (25th), 930 kW (50th) and 1,113 kW (75th).

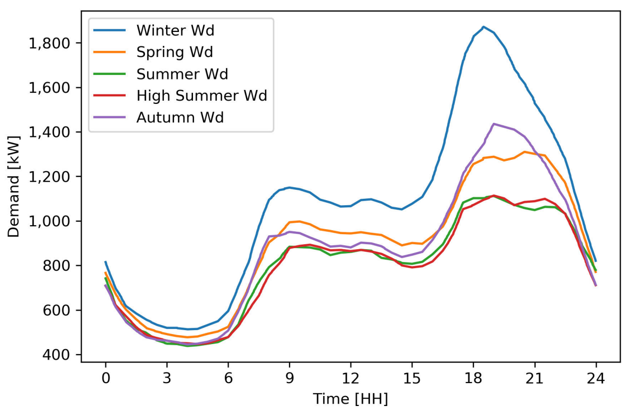



**FIGURE 3. 1-minute electric demand in weekdays per season in the simulated IEEE 34-bus test feeder. This feeder is originally provided for static analysis. The dynamic (timeseries) simulation uses the per-unit load profiles available in [38] estimated with the original load characteristics of the feeder.**

In this study, distributed PV and grid-scale BESS are deployed in the feeder considering six cases (see Section II-A2) and fifteen PV penetration scenarios (see Section II-C). In the IEEE 34-bus test feeder, PV elements are connected to eight buses to represent multiple distributed

PV systems connected downstream of those buses and a grid-scale BESS is also deployed, whose location results from an optimisation solution presented in Section III. The actual location of the distributed PV in the feeder is shown in Fig. 4, where the possible buses considered for the grid-scale storage are highlighted.

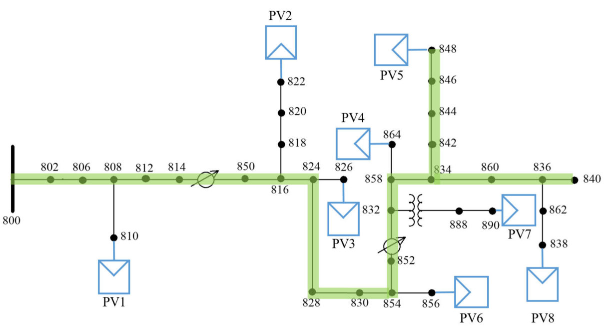



**FIGURE 4.** Single-line diagram of the studied IEEE 34-node test feeder with distributed PV and the feasible 3-phase buses considered to host grid-scale BESS.

### C. CASES AND SCENARIOS FOR DISTRIBUTED PV PENETRATION AND GRID-SCALE STORAGE

#### 1) CASES

Besides the base case without any distributed PV deployed, six variations of four cases are investigated in the IEEE 34-node test network, these are: (i) PV deployment using standard inverters with constant power factor output; (ii) PV inverters with constant power factor and grid-scale BESS; (iii) PV inverters with smart Volt-Var control; and (iv) PV inverters with Volt-Var control and grid-scale BESS with peak-shaving and Volt-Var control. The cases analysed are summarised in Table 5 and the control strategies for the distributed PV and the grid-scale battery are described below.

**TABLE 5.** Cases investigated for the distributed PV and grid-scale storage.

| Case Name | Description |
|---|---|
| Base | Feeder without PV nor energy storage systems |
| PV PF | PV with constant/fixed PF unity |
| PV PF 0.95 ind | PV with constant/fixed PF 0.95 inductive |
| PV PF 0.95 cap | PV with constant/fixed PF 0.95 capacitive |
| PV PF + BESS | PV with fixed PF unity and BESS in optimal bus |
| PV VV | PV with Volt-Var control |
| PV VV + BESS | PV with Volt-Var control and BESS in optimal bus |

#### 2) SCENARIOS

The simulations evaluate multiple scenarios regarding distributed PV penetration. Each of the PV generation profiles deployed in the network corresponds to a different annual per unit (kW/kWp) profiles modelled in the city of Belfast and part of the metropolitan area, where the geographical distance among the locations is similar to the distance of the cabling in the IEEE 34-bus system. Thus, a total of 8 PV generation profiles at 1-minute resolution where modelled using satellite-based irradiance data from the Copernicus atmosphere monitoring service all-sky radiation service [40]. The procedure to convert solar irradiance observations into power output used the model proposed by Huld *et al.* [41] for silicon technology modules and Faiman's model [42] for temperature correction of power output. Details of these models are available in [41] and [42], respectively.

Table 6 presents the characteristics of the PV systems connected to the IEEE 34-bus system. It is worth noting that using multiple time-series permits different PV generation profiles across the tested network with a per-unit power output data which can be scaled for each PV penetration scenario. The resolution of 1-minute simulation steps permits observing the full-operation in network infrastructure (e.g., in-line voltage regulators) when PV is present [25]. In addition, using 1-minute PV profiles better captures the variability of solar resource compared to traditional hourly timesteps used in the yearly-based simulations. Concurrently, the time span of the simulation over 1 year permits illustrating seasonal variabilities and uncertainties when compared to single-day simulation studies focused on worst-case scenarios.

**TABLE 6.** Characteristics of the distributed PV systems.

| PV element | Bus | No. of Phases | Voltage (kV) | Connection |
|---|---|---|---|---|
| PV1 | 810.2 | 1-phase | 14.376 | Wye |
| PV2 | 822.1 | 1-phase | 14.376 | Wye |
| PV3 | 826.2 | 1-phase | 14.376 | Wye |
| PV4 | 864.1 | 1-phase | 14.376 | Wye |
| PV5 | 848 | 3-phase | 24.9 | Delta |
| PV6 | 856.2 | 1-phase | 14.376 | Wye |
| PV7 | 890 | 3-phase | 4.16 | Delta |
| PV8 | 838.2 | 1-phase | 14.376 | Wye |

The solar systems deployed in multiple locations of the network have a total PV capacity that depends on the scenario of PV penetration level. In this paper, we evaluate 15 scenarios for PV penetration: 5% to 75% in 5% steps. The penetration level is defined in terms of energy from the total electric demand (including losses) in the base case and considering an average annual PV production of 887 kWh/kWp, which is the mean value of the 8 PV systems. It is assumed that the estimated PV capacity is evenly distributed across the 8 connections with distributed PV unless a capacity constraint would occur (e.g., transformer or line loading limits). The resulting PV capacities per scenario are presented in Table 7, where the capacity of PV systems 7 is limited to 349 kWp after 35% PV penetration in order to avoid over-loading the step-down transformer (500 kVA with a power factor of 0.8) supplying that zone.

### D. CONSIDERATIONS FOR THE ECONOMIC ASSESSMENT OF THE NETWORK

The technical evaluation of the grid-scale BESS addresses the balance of energy for real and reactive power, the reverse power flow, and the maximum hosting capacity due to voltage violations. In addition, the variations in the duty cycle

**TABLE 7.** Solar PV capacity per scenario in terms of energy as defined from the base case without PV and capacity for each of the PV systems simulated in the network.

| PV penetration level | Demand to cover (MWh) | Total equivalent PV capacity (kWp) | PV systems 1-6, 8 (kWp) | PV system 7 (kWp) |
|---|---|---|---|---|
| 5% | 413.163 | 466 | 58 | 58 |
| 10% | 826.326 | 932 | 116 | 116 |
| 15% | 1,239.489 | 1,397 | 175 | 175 |
| 20% | 1,652.653 | 1,863 | 233 | 233 |
| 25% | 2,065.816 | 2,329 | 291 | 291 |
| 30% | 2,478.979 | 2,795 | 349 | 349 |
| 35% | 2,892.142 | 3,261 | 416 | 349 |
| 40% | 3,305.305 | 3,726 | 482 | 349 |
| 45% | 3,718.468 | 4,192 | 549 | 349 |
| 50% | 4,131.631 | 4,658 | 616 | 349 |
| 55% | 4,544.795 | 5,124 | 682 | 349 |
| 60% | 4,957.958 | 5,590 | 749 | 349 |
| 65% | 5,371.121 | 6,055 | 815 | 349 |
| 70% | 5,784.284 | 6,521 | 882 | 349 |
| 75% | 6,197.447 | 6,987 | 948 | 349 |

**TABLE 8.** Capital and operational expenditures and financial variables for the economic assessment of grid-scale BESS.

| Variable / Parameter | Cost / Value | Source |
|---|---|---|
| Cost of battery system – battery pack | 122 GBP/kWh$_{dc}$* | BNEF [45] |
| Cost of battery system – battery power | 244 GBP/kW$_{dc}$* | BNEF [45] |
| BESS Installation Labour | 62 GBP/kWh$_{dc}$* | IRENA [46] |
| Operation and Maintenance BESS | 1.5% cost | Lazard [47] |
| Contingency | 4% cost | - |
| Grid Connection Chargers | 5,659 GBP (until 2 MW)<br>8,488 GBP (over 2 MW) | NIE Networks [48] |
| Insurance rate (annual) | 1% | SAM [49] |
| Taxes on property (annual) | 1% cost | SAM [49] |
| Battery Replacement | Every 10 years | PNNL [33] |
| Battery Performance Degradation | 0.5% per year | PNNL [33] |
| Real discount rate | 6% | NREL [50] |
| Inflation rate | 2% | Bank of England [51] |

*1 GBP = 1.30 USD

of in-line voltage regulators due to PV integration are also estimated.

Besides this technical evaluation of grid-scale BESS in mitigating grid constraints and violations, the economic profitability of grid-scale storage is assessed according to: (i) the BESS costs; (ii) the additional cost of replacing electrical infrastructure (i.e. voltage regulators); (iii) the equivalent avoided cost from $CO_2$ emissions in the network; and (iv) the revenue from grid services provided. The results are reported for a one-year period, and are evaluated with the following metrics: (i) net present value (NPV); (ii) discounted payback period; (iii) internal rate of return (IRR); and (iv) profitability index (PI). The NPV and the discounted payback period are used to assess the economic profitability of the grid-scale BESS project. In addition, two common corporate finance metrics, such as the IRR and the PI, are also used. The IRR is defined as the real discount rate that makes the present value of the future cash flows equal to the investment. The PI indicates the value you are receiving in exchange for one unit of currency invested and it is defined by Eq. (18) [43], where the project should be accepted with a PI higher than unity.

$$PI = 1 + \frac{NPV}{C_0} \tag{18}$$

### 1) CAPITAL AND OPERATIONAL COSTS OF GRID-SCALE BESS

The estimation of the cash flow and economic metrics of the grid-scale BESS as a financial asset requires multiple inputs regarding the capital and operational expenditures. The capital costs include direct costs, such as the costs of the batteries, and indirect costs like labour. In addition, the initial capital investment includes a contingency budget and the cost of the grid connection agreement.

The annual operational expenditures are defined as a percentage of the capital costs: operation and maintenance costs are 1.5%; the insurance is 1%; and the taxes on the property are 1%. The capital and operational costs are shown in Table 8. Moreover, the electricity consumed in idle state by the BESS is priced at a different electricity import rate depending on the period of the year as defined in Table 9 [44]. Only the electricity in idle state is assumed as a fuel cost, since the BESS response is based on the network's demand in order to provide grid services. A project's lifetime of 25 years is considered with a real discount rate of 6%. A replacement of the batteries every 10 years is considered, which is constant during the time horizon of the study. The batteries are considered with a degradation rate in their performance of 0.5% per year [33].

**TABLE 9. Electricity charges for energy consumed by the grid-scale BESS. Source: SONI [44].**

| Period of year | Electricity Charge (p/kWh) |
|---|---|
| November to February (16:00 h to 19:00 h) | 1.792 |
| November to February (8:00h to 20:30h) | 1.480 |
| November to February (20:30h to 22:30h) | 1.070 |
| November to February (22:30h to 8:00h) and March to October | 0.136 |

The initial capital or investment cost ($C_0$) of the project depends on the direct cost of the batteries, electric material, labour and installation. In addition, there are other indirect costs for the development of the project, such as grid connection charges ($C_{gc}$) and contingency budget ($C_{cnt}$). The initial investment including all these terms can be estimated using Eq. (19) [46].

$$C_0 = (P_{BESS} \cdot C_{PC} + E_{BESS} \cdot C_{EC} + C_{gc}) \cdot (1 + C_{cnt}) \quad (19)$$

where $P_{BESS}$ is the rated power of the BESS in kW, $C_{PC}$ is the power cost per kW, $E_{BESS}$ is the rated energy of the BESS in kWh, and $C_{EC}$ is the energy cost per kWh including the cost of the batteries, the labour and installation costs. The fixed annuity during the lifetime of the project $N$ is defined from the investment cost and the real discount rate $i$ following Eq. (20) [46].

$$A_{ESS} = \frac{C_0 \cdot i}{1 - (1+i)^N} \quad (20)$$

For the economic assessment, an estimation of compensation rates is proposed so that it would return positive economic profitability to the centralised BESS investment in exchange of the provision of real and reactive power supply. The approached used to determine the compensation rates is through a break-even point that equals the annual average compensation of the centralised BESS for real and reactive power supply and the total costs over the life span of the project is estimated. This break-even point is given by the equality in Eq. (21):

$$\sum_{y=1}^{N} \overline{PY_y^P} + \overline{PY_y^Q} = A_{ESS} \cdot N + C_{op} \quad (21)$$

where $\overline{PY_y^P}$ denotes the average compensation paid for real power each year and it is given by Eq. (22). $\overline{PY_y^Q}$ denotes the average compensation paid for reactive power supply each year and it is defined by Eq. (23). $C_{op}$ are the total operational costs, including maintenance and spares, during the whole lifetime of the project. In the average economic compensations, the energy is estimated from the effective power output, both real and reactive, based on the timestep $\Delta t$, where these are positive values and the units are pence/kWh for real power supply ($PY_{kwh,t}$) and pence/kvarh for reactive power supply ($PY_{kvarh,t}$). The annual variation in power supply of the battery correlates with the battery performance degradation rate specified in Table 8 for each year $y$ of the project's lifespan ($N$).

$$\overline{PY_y^P} = P_{t,eff,y}^{BESS} \cdot \Delta t \cdot PY_{kwh,t} \quad (22)$$

$$\overline{PY_y^Q} = Q_{t,eff,y}^{BESS} \cdot \Delta t \cdot PY_{kvarh,t} \quad (23)$$

### 2) COSTS OF THE ELECTRICITY NETWORK

Besides the costs of the grid-scale BESS, the economic assessment considers other costs of electrical infrastructure, such as the maintenance and replacement of the in-line voltage regulators present in the network. The integration of distributed PV may change the duty cycles of the voltage regulators compared to the base case. Thus, a prorated cost of the in-line voltage regulators during the project's lifetime is estimated considering a price of 25,131 GBP[1] per phase of the regulator [52] and an additional maintenance cost of 5% of the total cost, i.e. 1,256.55 GBP [53]. The lifetime of the in-line voltage regulators is estimated from: (i) an scheduled maintenance intervention for the tap changers in voltage regulators every 100,000 cycles or operations; and (ii) a replacement of the tap changers or the voltage regulators every 500,000 cycles or operations [54] or 35 years, whichever earlier.

The avoided cost of $CO_2$ emission trading system allowances is estimated for the 25-year period of the grid-level BESS. This avoided cost is considered as an income related to reduction of electricity from the grid due to local generation of distributed PV in the network, which is subject to the PV performance degradation of 1% per year. The annual net PV generation (PV generated minus energy in reverse power flows/curtailed) is used, together with a cost per tonne of $CO_2$ of 44 GBP/t as for the median value of future estimates for 2030[2] [55] and the grid electricity is assumed of 339 $gCO_2$/kWh, which corresponds to the latest available average carbon intensity of grid electricity in Northern Ireland (year 2018) [56].

### 3) REVENUE FROM PROVIDED GRID SERVICES

The services considered by the BESS that provide with revenue are: (i) real power supply; and (ii) voltage control/reactive power supply, which are common services provided by energy storage technology for power systems applications [16]. In addition, the temporal scale of 1-minute resolution in the simulation makes feasible the consideration of both power- (e.g., voltage control) and energy-related (e.g., real power supply) services.

In Northern Ireland, there not currently exist distribution-specific services. Therefore, the revenue considered is that equivalent from transmission-specific services. Nevertheless, the economic assessment includes in Section V-C and exploratory analysis of the annual mean prices for real and reactive power supply in distribution-specific services that would enable the profitability of grid-scale BESS like the one investigated.

[1] A cost of 30,000 CHF with an exchange rate of 1 CHF = 0.84 GBP.

[2] 32-65 EUR/t, median 48.5 EUR/t with an exchange rate of 1 EUR = 1.1 GBP.

For the service of real power supply through energy arbitrage performed by the battery system, the income is considered as a payment for the energy provided (i.e. GBP/MWh) with the price per unit corresponding to the day-ahead market price for the same delivery period as provided by the Irish electricity market operator [57]. The data used corresponds to the year 2019. Although the use of day-ahead market electricity prices does not reflect the changes in the intra-day and balancing markets, it can well serve as an input for an estimate of real power revenue.

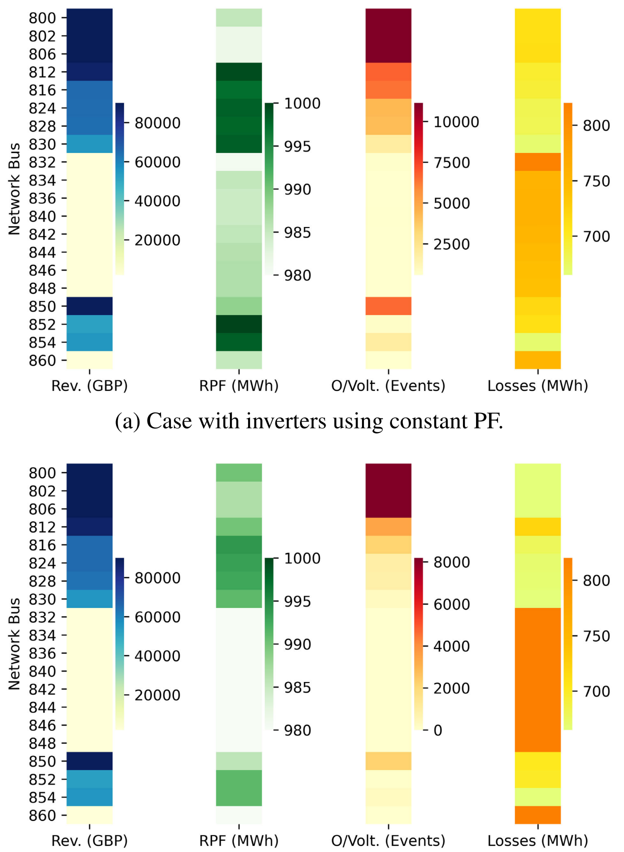
For the service of voltage control and reactive power supply, the payment is considered in return of the services of steady state reactive power considered in the Irish SEM market, which has a per unit payment equal to 0.23 GBP/Mvarh [58].

## III. SITTING DECISION OF GRID-LEVEL STORAGE SYSTEM

The results regarding the siting optimisation problem for the grid-level storage system are presented in this section. The global optimal solution includes four objective functions involving the annual total economic revenue from reactive and real power supply, the annual energy fed back in reverse power flows (or annual energy curtailed if that energy was not to be allowed to flow upstream of the MV substation), the annual number of over-voltage events, and the electricity losses in the network.

The impact of the grid-scale BESS location on the objective variables, before normalising, can be observed for each considered bus and the four variables in Figure 5. The economic revenue reveals that buses downstream of the in-line voltage regulator no. 2 benefit from much lower revenue levels (circa 2,000 GBP a year) than those upstream (around 90,000 GBP a year), with the highest being bus 806 in both cases of PV inverters' control. Regarding the reverse power flow or curtailed energy, it can be observed how this variable is highly affected by the inverters' control strategy. In presence of inverters using constant PF, the energy in RPF is higher than with Volt-Var control, since part of the inverter's capacity rating is used for reactive power dispatch. For the Volt-Var case, the annual revenue and RPF energy follow a positive relationship, since the grid-scale BESS observes less local solar generation and it has less energy to perform energy arbitrage services based on network conditions. The number of over-voltage events and the annual energy in network losses are similar in both subfigures with slightly higher losses in the case with Volt-Var control. The lowest values for the voltage violations and the highest for the losses are, again, found downstream of the in-line voltage regulator no. 2, which suggests that the over-voltage violations occur in that zone of the network.

Among the considered buses, bus 814 was discarded as a feasible solution as it presented convergence issues in the control algorithm between the grid-scale BESS and the in-line voltage regulator. From the remaining 20 buses considered,



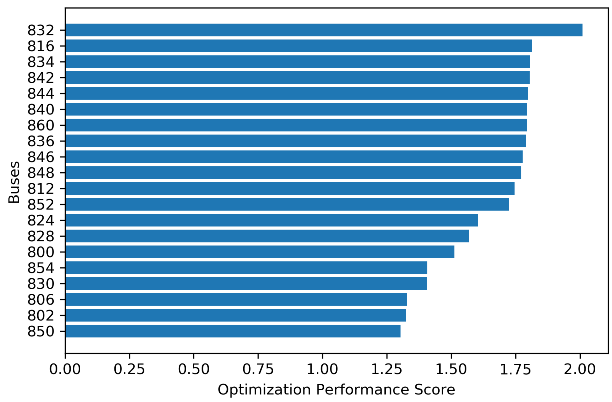

(a) Case with inverters using constant PF.



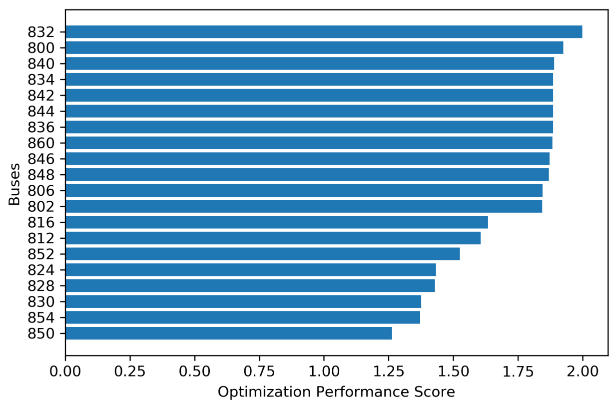
(b) Case with inverters using Volt-Var.

**FIGURE 5. Variables of the objective functions for each bus considered in the siting optimisation problem for a PV penetration of 40% in the case of PV inverters using (a) constant PF and (b) Volt-Var control. The colour intensity corresponds to the value of the variable. The global optimal network bus aims to maximise revenue (Rev.) and minimise reverse power flow (RPF), occurrence of over-voltage events (O/Volts.) and losses.**

the minimum normalised score and thus, the global optimal solution of the no-preference, multi-parametric model is bus 850 as observed in Figure 6. The solution for bus 850 is common for the presence of both PV inverters using constant PF and Volt-Var control. However, the second and third ranked buses differ in each case. Bus 802 is the second best when using constant PF, it however ranks mid-table when the PV inverters use Volt-Var. This performance in bus 802 illustrates the impact of smart control capabilities in PV inverters. The second overall best bus is bus 830, which ranks third for the PV VV case and fourth for the PV PF case. In contrast, the worst bus to locate the grid-scale BESS is bus 832, which is between the regulator no. 2 and the step-down transformer. Thus, following the solution of the optimisation model, the location of the grid-scale BESS can be defined in bus 850 and the techno-economic assessment with such network layout is presented in the remainder of the paper. The final layout of the IEEE 34-bus network with distributed PV and grid-scale BESS is illustrated in Figure 7.




(a) Case with inverters using constant PF.




(b) Case with inverters using Volt-Var.

**FIGURE 6.** **Performance scores for the grid-scale BESS siting optimisation problem in the case of PV inverters using (a) constant PF and (b) Volt-Var control. The global optimal location corresponds to the bus that minimises the score based on the normalised variables considered in the no-preference optimisation method. Bus 850 is the best performing bus in both cases.**

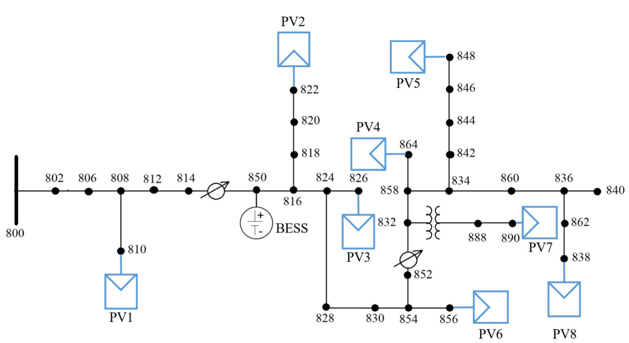



**FIGURE 7.** **Single-line diagram of the IEEE 34-node test feeder with distributed PV and the grid-scale BESS located in bus 850, the global optimal solution.**

## IV. TECHNICAL PERFORMANCE OF GRID-LEVEL STORAGE SYSTEM IN PRESENCE OF DISTRIBUTED PV

This section presents the results of energy- and voltage-related variables and parameters in the distribution network with a

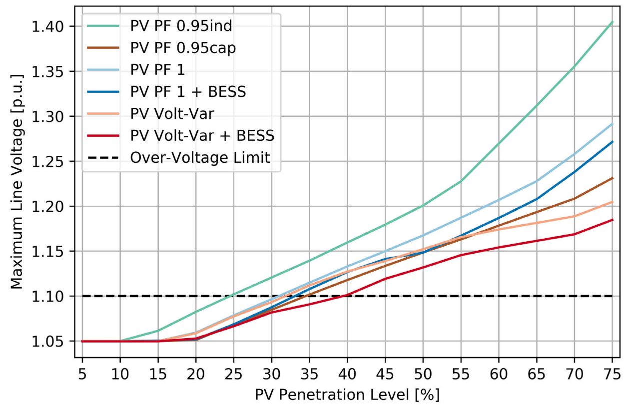



**FIGURE 8.** **Maximum line voltage in the network per case as function of PV penetration level.**

focus on the technical performance of the grid-level BESS.[3] Section IV-A begins by presenting the voltage violations throughout the 1-year simulation, which lead to estimating the maximum PV hosting capacity (HC) in the network. Then, Sections IV-B and IV-C continue with the energy balances for real and reactive power in the network, respectively, analysing the response as function of PV penetration up to the levels of the maximum hosting capacity. Finally, the changes in the duty cycle of the voltage regulators due to PV penetration are evaluated regarding the maintenance requirements and earlier replacement needs as function of PV penetration.

### A. VOLTAGE VIOLATIONS IN THE NETWORK

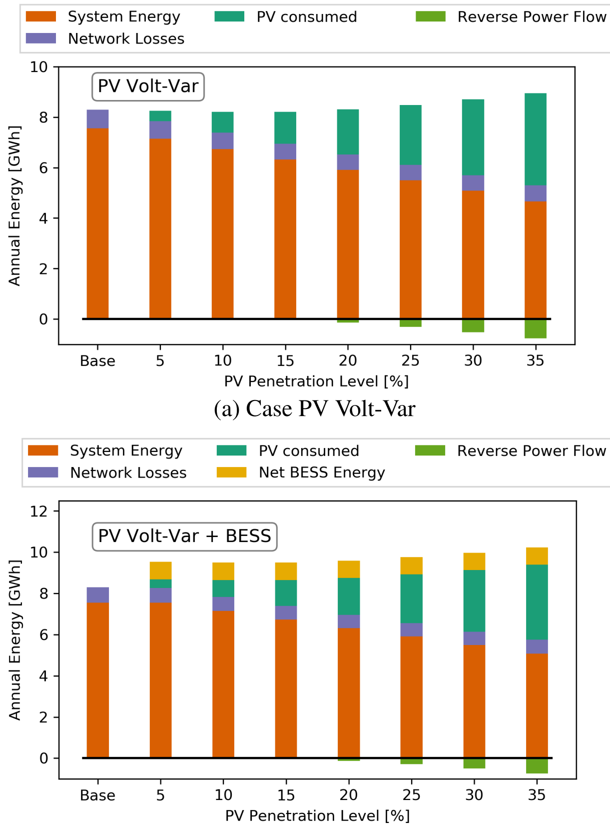
This section analyses the voltage violations, both under- ($\leq$ 0.85 p.u.) and over-voltage ($\geq$ 1.1 p.u.) events as function of PV penetration. The six considered cases are compared to the base case, which does not register any voltage violation. The assessment of the voltage violations in the network is the defining factor to establish the maximum PV hosting capacity of the network for each of the cases. The maximum voltage reported in the network as function of PV penetration is presented in Figure 8. It can be observed how over-voltage conditions are reported in all six cases for PV penetration levels larger than 35%. The lowest maximum PV hosting capacity is reached for PV PF 0.95 inductive at 20% PV. In contrast, the highest maximum PV is 35% for the case PV VV + BESS. The remaining of the cases find the maximum PV hosting capacity for a PV penetration of 30%. Among the cases with fixed PF, the case PF 0.95 capacitive responds similarly to the PF unity case. It is worth noting that the grid-scale storage enhances the hosting capacity for the case Volt-Var control, but it does not improve it for the fixed power factor control. The Volt-Var control in the inverters permits higher hosting capacity than constant power factor control, but only when storage is present in the network. The case

[3]From section IV on, the results with data about grid-scale BESS refer to the solution with the battery system in bus 850 as concluded from the result of the siting optimisation problem.

without energy storage and PV Volt-Var reports the same hosting capacity than the case of grid-scale energy storage and PF inverters, a maximum hosting capacity of 30%. The simulation results indicate that there are not under-voltage events in the network for any case nor PV penetration level. Thus, the maximum PV hosting capacity is solely determined from the over-voltage events in this network and it is summarised in Table 10. The analysis of the maximum voltage levels show that the location in the network where the maximum voltage levels are registered is bus 814 in all four cases, which corresponds to the location of the in-line voltage regulator no. 1. However, when the maximum voltage levels in the network occur, the minimum voltage levels are simultaneously found in bus 814, which highlights the effect that PV can have in highly unbalanced networks. The IEEE 34-node is originally unbalanced, but the PV connected to single phases upstream and downstream of bus 814 (e.g., PV1 in bus 810.2) makes it even more unbalanced and these are probably responsible for the hosting capacity limitation in that bus.

**TABLE 10. Summary of maximum PV hosting capacities in the network attending to voltage violations, including maximum voltage and bus of over-voltage event.**

| Case | Max. HC | Max. Voltage (p.u.) | Bus O/V |
|---|---|---|---|
| PV PF (unity) | 30% | 1.096 | 814 |
| PV PF 0.95 ind. | 20% | 1.082 | 814 |
| PV PF 0.95 cap. | 30% | 1.085 | 814 |
| PV Volt-Var | 30% | 1.093 | 814 |
| PV PF (unity) + BESS | 30% | 1.087 | 814 |
| PV Volt-Var + BESS | 35% | 1.091 | 814 |



(a) Case PV Volt-Var

(b) Case PV Volt-Var + BESS

**FIGURE 9. Annual energy balance of real power in the network as function of PV penetration with distributed PV using Volt-Var mode, and without (a) and with (b) grid-scale BESS.**

## B. ENERGY BALANCE FOR REAL POWER

This subsection covers the real energy balance in the network and the changes in the total annual energy supply as function of PV penetration, including the PV generated, the losses in the network and the net real power supply of the grid-scale BESS. This is followed by further results about the energy losses in the network.

### 1) REAL POWER BALANCE

The real power supplied by the grid varies depending on the amount of locally produced solar energy. The annual balance of energy as function of PV for the cases with Volt-Var operation is shown in Figure 9 and includes the energy coming through the substation (denoted as 'system energy'), the real power losses in the network, the PV energy consumed in the network and the PV generation surplus, which is fed back to the grid as a reverse power flow or it could also represent the energy curtailed.

The base case provides a reference for the rest of scenarios, and it has a total annual gross energy of 8.29 GWh from which 8.98% correspond to network losses. In Figure 9-a, it is possible to observe the progressive reduction from the electricity supplied by the grid as PV local generation increases and it is consumed within the network. Every 5% of PV in the network permit a reduction in the system energy of an additional 0.412 GWh. As PV penetration increases, reverse power flow would occur after 10% PV penetration. The energy categorised as 'reverse power flow' can also be considered as the curtailment of solar energy in order to avoid feeding back energy into the grid upstream of the MV substation. In addition, the network losses, which are examined further later in this section, reduce moderately as PV penetration increases.

For the case with grid-scale energy storage in Figure 9-b, the net energy power flow of the battery comes as a new variable to the energy balance. The net BESS energy accounts for the energy consumed while charging (i.e., as a load) plus the total BESS energy losses (i.e., inverter's losses and idle state losses) and subtracting the energy supplied/discharged (i.e., as a generator). The figure shows that the grid-scale BESS acts more as a load than a generator and that its contribution is nearly constant as function of the PV penetration at a value around 0.85 GWh. Compared to the cases without storage, the BESS reduces the energy fed back into the grid around 5%.

### 2) NETWORK LOSSES

The integration of solar PV energy affects the real power losses in the network as the demand is covered by local

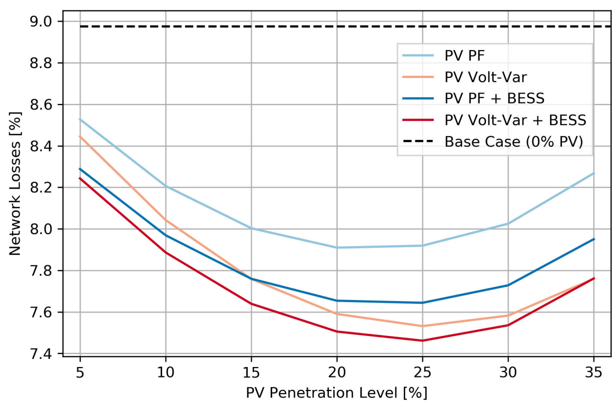
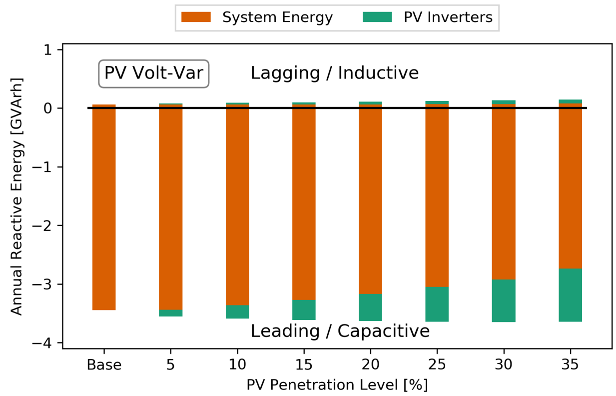
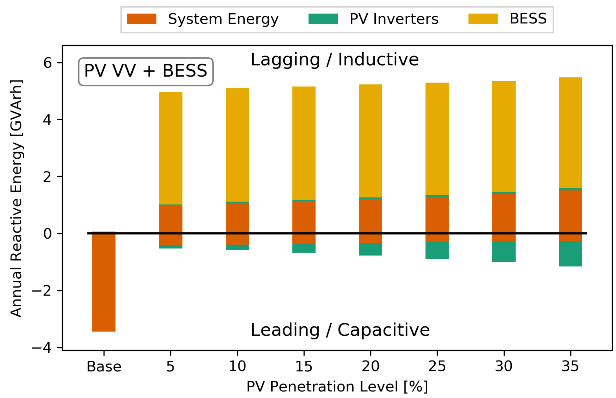



**FIGURE 10. Percentage of real power losses in the network per case as function of PV penetration.**




(a) Case PV Volt-Var




(b) Case PV Volt-Var + BESS

**FIGURE 11. Annual energy balance of reactive power in the network as function of PV penetration for the case with PV inverters using Volt-Var mode, and without (a) and with (b) grid-scale BESS.**

generation and there is lower loading in power lines and other electric infrastructure and, in consequence, reduces the resistive losses. In order to obtain better insights about the evolution of the percentage network losses compared to the base case, the percentage of resistive losses for each case as function of the PV penetration level is presented in Figure 10. It can be observed that the losses follow concave upward curve shapes, which are below the base case losses (i.e. 8.98%).

The case with grid-scale storage and PV using Volt-Var controlled inverters reports the lowest losses in the range assessed, up to a penetration of 35%. The minimum of the identified concave upward curves are at 20% PV penetration for the cases PV PF (7.90%) and 25% for the cases PV PF + BESS (7.64%), PV Volt-Var (7.53%) and PV Volt-Var + BESS (7.46%). This minimum losses represent a reduction up to 16.88% compared to the base case. Overall, the results suggest that both technologies of distributed PV can benefit the network in terms of energy losses and that grid-scale storage can further enhance the reduction of losses.

### C. ENERGY BALANCE FOR REACTIVE POWER

This section presents the balance of reactive energy by evaluating the contribution of the PV inverters and grid-level BESS as function of the PV penetration level. First, an overall power balance in the network is introduced, then a break-down of the contribution of the individual PV inverters deployed in the feeder is presented.

#### 1) REACTIVE POWER BALANCE

The annual balance of reactive power is presented below for each case as function of the PV penetration level. In Figure 11-a, it can be observed for the cases without grid-level storage how the system's reactive energy is predominantly of capacitive nature. The PV inverters provide both reactive and capacitive reactive energy, particularly the latter. The leading reactive energy of the inverters contributes to compensate higher voltage levels produced across the network buses when injecting PV's real power. In addition, the provision of reactive power by the PV inverters helps compensate the voltage fluctuations occurring during times without solar generation. For the PV VV case, the capacitive reactive energy contribution of the PV inverters goes from 3.2% (0.11 Gvarh capacitive at 5% PV) to 32.7% (0.91 Gvarh capacitive at 35% PV) of the total capacitive energy of the network. Similarly, the PV inverters supply from 24.9% (64 Mvarh at 35% PV) to 67.2% (49 Mvarh at 20%) of the inductive reactive energy.

When the grid-level energy storage system is integrated (see Figure 11-b), the BESS solely provides lagging reactive energy, which responds to the need of the network for a compensation to higher voltage levels. The grid-level storage system increases considerably the volume of lagging reactive energy and it presents a similar behaviour for all the scenarios. The addition of grid-level BESS minimises the need for capacitive energy from the grid. Yet, the grid provides a small amount of capacitive energy for all PV penetration levels, whose consumption occurs in the main branch of the network up to bus 814. The net reactive demand evolution is similar in all the PV penetration range.

### 2) REACTIVE POWER SUPPLY OF PV SYSTEMS

Given the substantial contribution of the PV inverters in the reactive energy balance as observed in Figure 11, the analysis of the reactive energy supply from the PV inverters can be further studied by looking at the individual contribution of each inverter. For the purpose of analysing a break-down of the reactive energy balance of the PV inverters, the scenario with a PV penetration of 30% is selected. This PV penetration level corresponds to the maximum PV hosting capacity for the cases PV PF, PV VV, PV PF + BESS and it is a feasible scenario of PV VV + BESS. For the 8 PV systems in the simulation, the distribution of the reactive power consumption for each case and system is illustrated in Figure 12. For the cases with constant power factor, the consumption of the inverters is null. Moderate differences are however observed in most of the PV systems for the Volt-Var mode with and without grid-scale BESS.

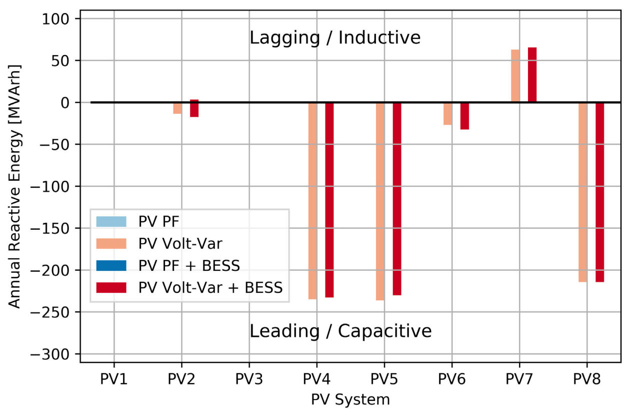



**FIGURE 12. Annual Reactive Energy Consumption of the PV inverters for the scenario with 30% of PV penetration.**

Those inverters with Volt-Var operation adapt their output to the local characteristics of the bus where they are connected. Consequently, the differences in the dispatch of the PV inverters with Volt-Var control depend on the location within the network. PV1 requires near-zero reactive energy compensation due to the proximity to the substation transformer with constant 1 p.u. supply. Similarly, PV3 also requires near-zero reactive energy operation. In this case, it may be because of its proximity to voltage regulator 1. The results suggest that the locations of PV1 and PV3 seldomly record voltage levels outside of the operational limits of PV inverter Volt-Var control (from 0.97 p.u. to 1.03 p.u., see Table 2) throughout the year. In contrast, the rest of the PV systems require a substantial reactive energy contribution to locally compensate voltage levels. PV4, PV5 and PV8 require the most significant dispatch of capacitive reactive energy and a common characteristic of these PV systems is that these are the furthest to the substation. As a result of both, lightly-loaded, long lines and PV penetration, the inverter helps compensate the voltage level by consuming capacitive reactive energy. PV2 and PV6 behave similarly but their location requires much less reactive energy, with PV2 dispatching inductive reactive energy at times. PV7, which is located downstream of the 4.16 kV step-down transformer, is the only PV system dispatching only inductive reactive energy. While the deployment of the grid-scale BESS helps ease the reactive dispatch of heavily duty-cycled inverters (e.g., PV4 and PV5), it leads to increasing the reactive dispatch needs for other near-by buses (e.g., PV2 and PV6). Thus, it can be noted that the characteristics of the network have a direct effect and determine the behaviour of the inverters connected to it.

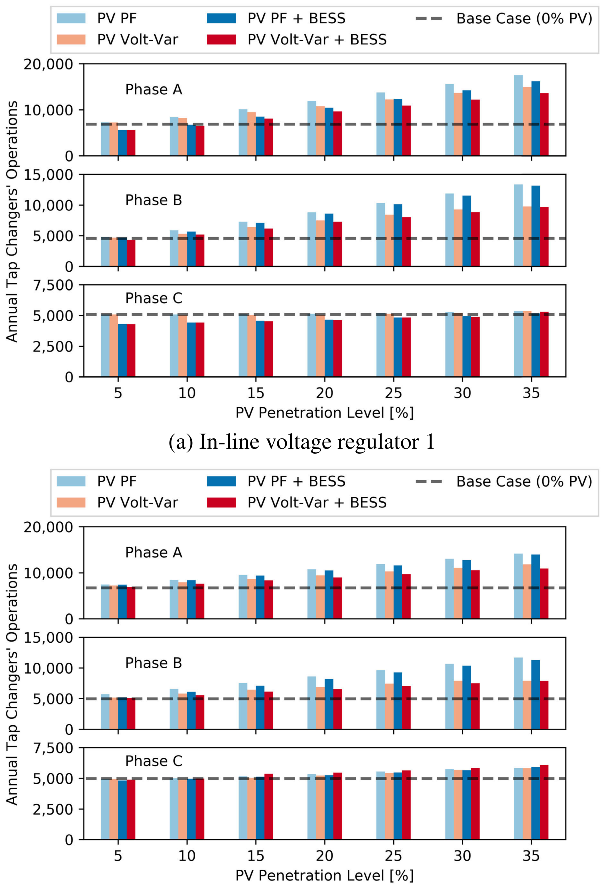
## *D. OPERATION OF IN-LINe VOLTAGE REGULATORS*

The injection of PV power can increase the voltage level at the point of connection and the surrounding buses. In addition, the rapid fluctuations that PV power output due to irradiance variability can also affect the voltage levels across the network. This impact can be reflected in electrical infrastructure, such as voltage regulators. This section analyses the variations in the duty cycle of the voltage regulators to evaluate how distributed PV and grid-scale BESS can alter their operation and lifetime.

The operations of the tap changers per phase in regulator no. 1 are shown in Figure 13-a for all cases up to 35% of PV penetration. The unbalanced nature of the network can be observed comparing the duty cycle across phases, where phase A has the highest number of operations throughout the year. The annual cycles of operation progressively increase as PV penetration grows and, with the exception of phase C, the operation per phase are moderately higher than the base case, where the regulator 1 has 6,881 operations/year in phase A, 4,541 operations/year in phase B and 5,091 operations/year in phase C. It can be inferred that the Volt-Var control mode of PV inverters is directly responsible for the reduction in the cycles of operation and that grid-scale BESS further reduces the operation of the voltage regulator. The contribution of the grid-scale BESS is enhanced by the proximity in the network to the voltage regulator no. 1.

Similarly, Figure 13-b shows the annual operations of the tap changers per phase in the regulator no. 2 as function of PV penetration level. It can be observed how in the base case, the regulator has a more balanced distribution of the annual tap changers' operations per phase, i.e. 6,731 in phase A, 4,980 in phase B and 4,993 in phase C. The impact of PV integration is similar to that described for the voltage regulator no. 1, that is, the presence of Volt-Var controlled inverters reduces the operations when PV is deployed. Grid-scale BESS has however a lesser effect in reducing the duty cycle of the voltage regulator no. 2, which even increases in phase C.

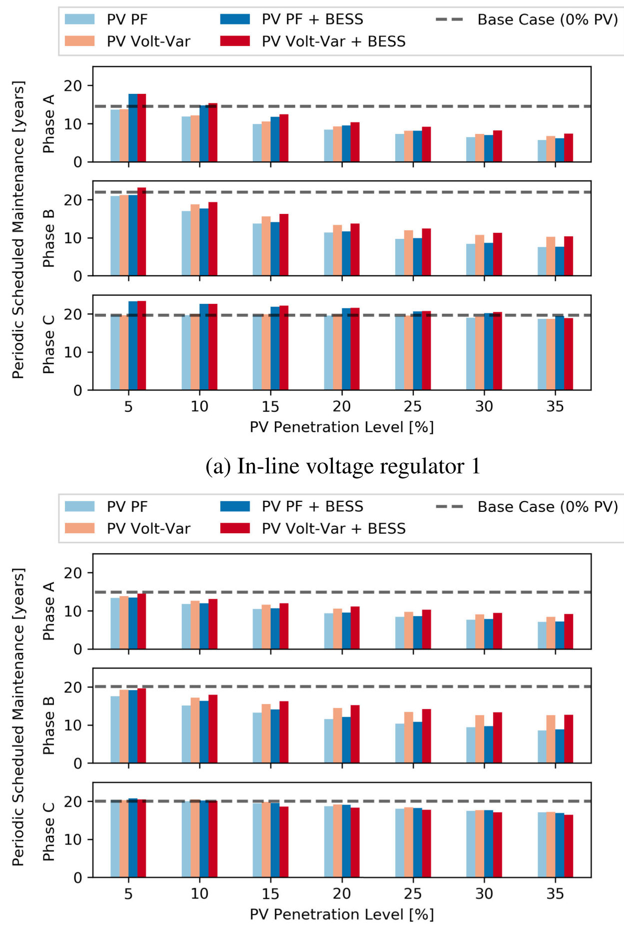
The cycles per phase of each in-line voltage regulators due to the distributed PV and grid-scale energy storage can be compared to the base case in order to evaluate the impact on maintenance requirements. The temporal variations in the scheduled maintenance interventions can be estimated by considering a routine maintenance interventions for the tap changers in voltage regulators every 100,000 cycles or operations [54]. Dividing these reference value by the cycles




(a) In-line voltage regulator 1

(b) In-line voltage regulator 2

**FIGURE 13. Annual number of operations of the tap changers per phase in the in-line voltage regulators of the network per case and as function of the PV penetration level.**




(a) In-line voltage regulator 1

(b) In-line voltage regulator 2

**FIGURE 14. Variation in the periodic scheduled maintenance interventions for the in-line voltage regulators of the network per phase, case and as function of the PV penetration level.**

per phase, a periodic, routine maintenance in the base case would be required between 14.5 to 22 years approximately. Similarly, the maintenance periods for each case and PV penetration can be estimated and the differences examined; these are presented in Figure 14-a for regulator no. 1 and in Figure 14-b for regulator no. 2.

Since the duty cycle of the in-line voltage regulators grows as PV penetration grows, the maintenance requirements have an inversely proportional relationship to the operation of the regulators. As a result, most of the cases lead to earlier maintenance and replacement interventions in the regulators.

For the voltage regulator no. 1, it is possible to observe that a PV penetration of 5% is the only value that would defer the intervention for all phases. Phase C is the least affected phase in regulator 1 and the case PV VV + BESS would defer the maintenance interventions for penetrations up to 30% inclusive. In contrast, Phase A is the most affected by the integration of PV and where at 30% and 35% PV (where the maximum PV hosting capacities occur), the maintenance would drop to every 6-7 years. Phase B would less affected than phase A, but the maintenance requirement would also drop to every 8.5-10 years at the maximum hosting capacities ranges. For the voltage regulator no. 2, the picture is similar, phase A is the most affected with maintenance required every 7.5-9 years, followed by phase B with maintenance needs every 9.5 to 12.5 years and the least impact is observed in phase C. Overall, the trend is that Volt-Var control defers the maintenance requirements compared to fixed (unity) power factor control. Grid-scale BESS also helps reducing the maintenance, particularly in phases where PV inverters are connected. For the simulated network, single-phase PV systems are solely connected in phases A and B (see Table 6). It is in those phases where it is possible to observe the better performance in the cases with Volt-Var control and grid-scale BESS.

### *E. SUMMARY OF THE TECHNICAL PERFORMANCE RESULTS*

Throughout this Section IV, the technical performance of the centralised BESS has been introduced. Below, a recap of the obtained results is presented before moving into the analysis of the economic performance in the next section.

#### 1) PV HOSTING CAPACITY DUE TO VOLTAGE VIOLATIONS

The analysis showed that the maximum PV hosting capacity in the network was determined by the occurrence of over-voltage events. The maximum line voltages reported across the network showed that the centralised BESS favours distributed small-scale PV penetration, and it enabled a further 5% PV share when smart PV inverters using Volt-Var control are present. Without smart PV inverters, the PV hosting capacity in the network can be enhanced by setting the inverters in unity or capacitive power factor. Although the maximum PV hosting capacity may remain the same without smart inverters, the centralised BESS helps reduce maximum voltage levels across the network for the same PV penetration as illustrated in Table 10.

#### 2) REAL POWER SUPPLY

The analysis of the real power balance illustrated that, overall, the centralised BESS acts as a load and presented a positive net energy consumption (around 0.85 GWh/year for any PV penetration level). Within its energy capacity, the centralised BESS also contributed to reduce the reverse power flow reaching the substation. It was also reported that PV reduces the network losses for any penetration level when compared to the base case, up to 16.88% losses reduction in the best case. The centralised BESS cuts down the network losses further than the cases without storage for any control type of the PV inverters. This was graphically illustrated in Fig. 10.

#### 3) REACTIVE POWER SUPPLY

The reactive power balance was highly influenced by the centralised BESS (see Fig. 11), which provides the majority of lagging reactive energy required in the network (around 0.7 GVArh/year for any PV penetration level). When distributed PV inverters incorporate Volt/Var control, the relative location of the PV inverters with respect of the network affects their reactive power supply requirements. In the studied network, PV inverters mainly dispached leading or capacitive reactive energy, which mitigated the injection of real PV power at their points of connection. It was shown in Fig. 12 that centralised BESS helps easing the needs for reactive power dispatch of heavily duty-cycled inverters in the network, while having the contrary effect in near-by inverters.

#### 4) EFFECT IN NETWORK INFRASTRUCTURE

The integration of PV was reported to increase the duty cycle of in-line voltage regulators in the network when compared to the base case without PV. An increased duty cycle in these network assets represents a devitation in their periodic maintenance interventions and their life time, which are required earlier than without PV presence. To that end, centralised BESS helped reduce the duty cycle of the in-line voltage regulators from few hundreds to thousands of cycles per year depending on the PV penetration levle and the case (with constant and Volt/Var PV inverters) as reported in Fig. 13. In consequence, centralised BESS partly mitigated the earlier wear and tear of the in-line voltage regulators, particularly those in highly loaded electric phases (see Fig. 14).

## V. ECONOMIC PERFORMANCE OF GRID-LEVEL STORAGE SYSTEM IN PRESENCE OF DISTRIBUTED PV

This section covers the economic profitability of the grid-scale BESS based on the revenue streams from real and reactive power supply. First, the annual revenue as function of PV penetration is analysed, and it is then complemented with relevant economic metrics for the storage system. The section continues by analysing the payment rates which would make profitable grid-scale energy storage systems in future distribution-specific services. Finally, the economic impact on the network from the integration of distributed PV and grid-scale energy storage is assessed.

### A. REVENUE STREAMS FROM REAL AND REACTIVE POWER SUPPLY

The revenue stream from the supply of real and reactive power follows the methodology described in Section II, where it is assumed that the grid-level BESS participates in the whole-sale electricity market for real power supply and the reactive power supply is paid at a constant rate of 23 pence/Mvarh as for the ancillary services conceived for generators within the Irish Single Electricity Market. This compensation would correspond to traditional transmission-specific services offered to large generation units.

The total revenue and the breakdown of revenue per type of energy is presented in Figure 15, where the grid-level BESS under presence of the PV inverters using Volt-Var control reports a slightly higher revenue. The figure shows how real power energy supply represents almost the totality of the income with a positive linear relationship with several slopes as function of the PV penetration. In the contrary, the reactive energy supply represents a small share of the revenue ranging from 890 GBP to 917 GBP per year. The revenue from reactive energy follow a concave down increasing trend, which is different for each inverter control

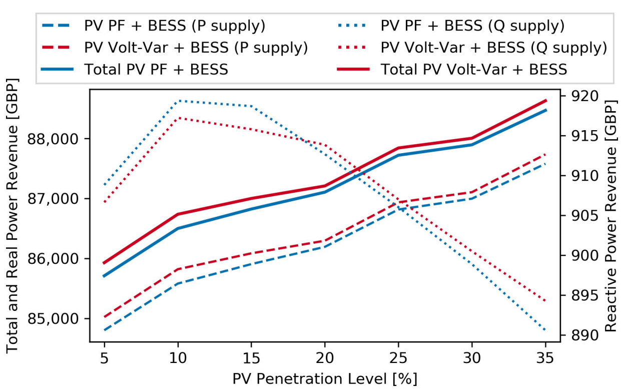



**FIGURE 15.** **Annual total and separated revenue of the grid-scale BESS for the supply of real and reactive power as function of PV penetration.**

**TABLE 11. Annual revenue and economic metrics for the grid-level BESS with a PV penetration equivalent to the maximum hosting capacity of the network for each of the cases.**

| Economic variable | PV PF + BESS (30% PV) | PV VV + BESS (35% PV) |
|---|---|---|
| Real Power Revenue (GBP) | 86,996.26 | 87,736.07 |
| Reactive Power Revenue (GBP) | 898.89 | 894.28 |
| Total Revenue (GBP) | 87,895.15 | 88,630.35 |
| NPV (GBP) | -365,612.18 | -354,445.64 |
| IRR (%) | -24.94 | -23.90 |
| Disc. PB (years) | N/A | N/A |
| PI | 0.629 | 0.639 |

strategy and the tipping points are 10-20% PV penetration depending on the case. The total revenue, which is very similar for both cases, ranges from 85,709 to 88,630 GBP per year.

Focusing on the economic revenue at the estimated maximum PV hosting capacities (see Table 10), the break-down of the revenue streams is presented in Table 11. The total revenue would reach nearly 90,000 GBP of which over 98.9% would come from real power energy dispatch and with differences between the cases below 800 GBP. The average payment for the supply of real power is 38.23 GBP/MWh (PV PF + BESS) and 38.52 GBP/MWh (PV VV + BESS).

### B. ECONOMIC PROFITABILITY METRICS

The economic profitability metrics for the grid-scale BESS are presented below for the maximum PV hosting capacity levels, i.e. 30% in presence of constant PF inverters and 35% when Volt-Var controlled inverters are deployed for the PV. The assessment includes the following metrics: (i) net present value (NPV); (ii) internal rate of return (IRR); (iii) discounted payback period (PB); and (iv) profitability index (PI). The metrics are estimated considering the battery operation and revenue of the first year during the lifetime of the project, which are then subject to degradation factor, discount rates, etc.

With the capital and operational costs introduced in Table 8 and Table 9, the resulting initial capital investment of the grid-scale BESS equals to 984,317.36 GBP, which turns into an annuity of 76,999.92 GBP during the life span of the project. The annual cost of the electricity consumed during idle state reaches 318.74 GBP (PV PF + BESS) and 316.77 GBP (PV VV + BESS) to which the annual O&M, taxes and insurance costs need to be added. All these costs lead to the economic metrics presented in Table 11. It can be observed that the grid-level BESS would not be economically profitable and would result in a negative profitability with a net present values around −350,000 GBP. A closer look to the cash flow over the 25-year period of the project in Figure 16 reveals that the main factor of the negative profitability of the grid-level BESS is the batteries' replacement in the years 10 and 20, which are large withdrawals. It can be also observed that, despite the BESS performance degradation, the higher electricity prices due to inflation progressively bring increased deposits and positive annual net cash flows after year 12.

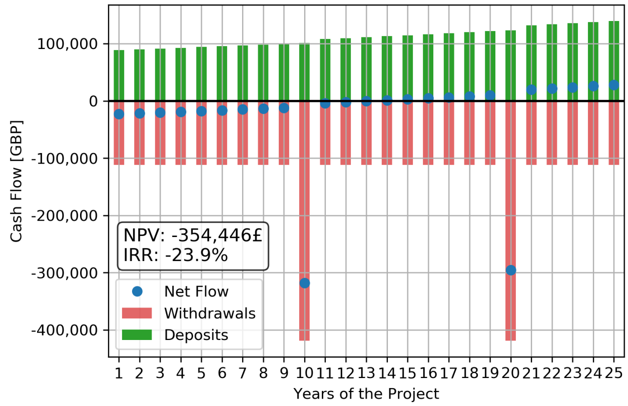



**FIGURE 16. Cash-flow for the grid-level BESS (case PV VV + BESS) for a PV penetration of 35%. After the 12th year, the net cash flow is positive. However, the replacements of the battery cells in the years 10 and 20 of the project penalise its economic viability.**

### C. FINANCIAL BREAK-EVEN THRESHOLD FOR THE REVENUE OF GRID-SCALE BESS

The economic metrics presented in the previous section show that grid-scale BESS is not profitable. The payments for the services to supply real and reactive power in the economic assessment corresponded to typical values that large generators with output in the range of MWs would be suitable to. These services can be illustrative to estimate the profitability with a current framework of TSO-level services. Nevertheless, these may not reflect the local value added by distribution-level, front-of-the-meter energy storage projects that can help locally manage DG. In this subsection, the annual average payment for the supply of real and reactive power are explored so that those distribution-specific services would make profitable the grid-scale BESS project.

Considering the capital and operational costs and financial variables in Table 8, the annual total revenue that would make produce the financial break-even point, where NPV=0 and PI=1, is estimated to be 112,032.65 GBP (PV PF + BESS) and 112,030.64 GBP (PV VV + BESS). From these annual revenues and with the real and reactive energy balances presented in Section IV, the range of prices for each type of energy that equal the PI=1 and NPV=0 can be estimated. The results are shown in Figure 17, where it is possible to observe how any annual average payment per unit for real power supply over 4.87 p/kWh would lead to a profitable grid-scale

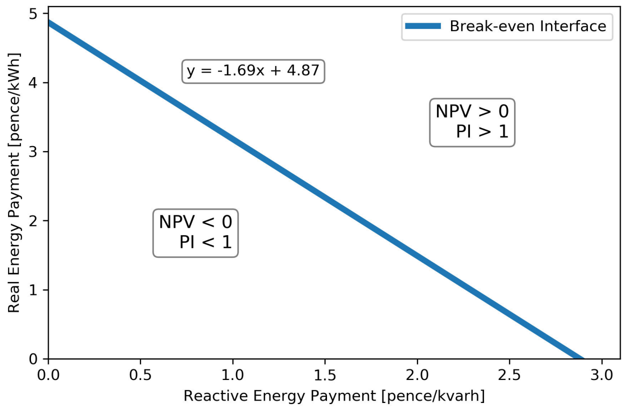



**FIGURE 17.** Financial break-even interface (NPV=0, PI=1) for the annual average real and reactive power received payment rates for grid-scale BESS. An annual average payment for real power supply higher than 4.87 p/kWh or for reactive power supply higher than 2.88 p/kvarh would make profitable the grid-scale BESS project considered.

BESS project. Similarly, any annual average payment per unit for reactive power supply over 2.88 p/kvarh would also produce economically beneficial results. The graph illustrates a wide range of possibilities for the definition of potential received payment rates for grid-scale BESS as exchange for the provision of local distribution-specific services.

### D. ECONOMIC IMPACT ON THE LOCAL POWER NETWORK AND ITS INFRASTRUCTURE

It was observed in Section IV-D that distributed PV penetration and the presence of grid-scale BESS have an impact on the operation of the in-line voltage regulators present in the network. As a result, additional or fewer maintenance interventions may be required throughout the life span of the components. Thus, this subsection examines the economic consequences of an increase in the duty cycles of voltage regulators during a 35-year period. The prorated costs in the maintenance and replacement of the in-line voltage regulators during 35 years are presented in Table 12 for each case at its maximum PV hosting capacity. The results show that PV PF is the case that increases the most the overall costs associated to the voltage regulators, up to 23.2% compared to the base case. For the same PV penetration, i.e. 30%, the case PV PF + BESS leads to 7.3% additional cost compared to the base case. For the cases with Volt-Var control, the additional costs are less than those with constant power factor operation. While the additional costs reported by the cases with and without storage are similar, i.e. 5.6% and 5.5%, respectively, the case PV VV + BESS would enable 5% of PV energy in the network. Thus, the result show the benefits of grid-scale BESS in reducing the economic impact on voltage regulators. Overall, considering the 35-year period, the cost variations due to PV integration are low to moderate regarding the periodic maintenance and earlier replacement of the voltage regulators.

**TABLE 13.** Avoided $CO_2$ emissions and avoided equivalent cost of $CO_2$ ETS credits over 25 years due to distributed PV penetration.

| Case | Avoided CO2 (t) | Eq. Cost CO2 ETS (£) |
|---|---|---|
| PV PF and PV VV (30%) | 14,816.34 | 651,919.99 |
| PV PF + BESS (30%) | 14,873.43 | 654,431.10 (+0.4%) |
| PV VV + BESS (35%) | 16,254.11 | 715,181.02 (+9.7%) |

Concurrently, the integration of PV in the network brings forward the decarbonisation of the network and there are additional avoided costs from the $CO_2$ emission trading credits acquired within the carbon dioxide emission trading systems (ETS). An estimate of the economic benefit derived from this decarbonisation of the network during a 25-year period is presented in Table 13 and hints large economic benefits. The results show that the extra PV hosting capacity enabled by the grid-level storage increases the avoided cost by 0.4% (2,511.11 GBP) in the PV PF + BESS case compared to the PV PF case, and by 9.7% (63,261.03 GBP) in the PV VV + BESS case.

Altogether, the lower impact on the in-line voltage regulators and higher avoided cost due to the decarbonisation of the network suggest that the network would benefit from the deployment of a grid-level BESS in combination to distributed PV, particularly if PV inverters with smart control capabilities are deployed.

## VI. SENSITIVITY ANALYSIS FOR GRID-LEVEL BESS

Following the technical and economic evaluation of the grid-level battery storage system, this section presents a sensitivity analysis that examines the variability of certain macro-economic parameters and the changes in the results if the battery system had different power output and energy capacity ratings. For the macro-economic variables, the focus is placed on the BESS costs per unit of energy and power, and the real discount rate. For the size sensitivity, the focus is on the economic profitability of the project.

### A. SENSITIVITY TO MACRO-ECONOMIC PARAMETERS

The sensitivity of the macro-economic variables in the project looks at the variations from −50% to +50% in the cost of BESS per unit of energy and per unit of power, and the real discount rate. In order to illustrate the changes in the economic value, the profitability index (PI) is illustrated as an overall metric, which if larger than unity would represent a profitable financial investment (see Eq. (18)).

The results are shown in Figure 18 and illustrate that the grid-scale BESS would turn into a profitable asset if the BESS cost per energy would drop 50% to 61 GBP/kWh or the overall BESS cost would drop at least 35% compared to the reference costs presented in Table 8. The grid-scale BESS would be profitable with a price per energy unit equal or lower than 79.3 GBP/kWh and the price per power unit equal or lower than 158.6 GBP/kW. The variations in the BESS cost per power unit and real discount rate would not be enough

**TABLE 12. Costs of the periodic maintenance and replacement of the in-line voltage regulators in GBP during a 35-year period and the variations in cost per case at the maximum PV hosting capacity.**

| PV penetration | | 0% | 30% | 30% | 30% | 35% |
|---|---|---|---|---|---|---|
| | Phase | Base Case | PV PF | PV VV | PV PF + BESS | PV VV + BESS |
| Reg. 1 | A | 26,900.66 | 54,626.82 | 29,898.72 | 30,127.42 | 29,867.06 |
| | B | 25,871.55 | 29,094.35 | 27,961.89 | 28,942.62 | 28,122.42 |
| | C | 26,113.43 | 26,189.95 | 26,160.93 | 26,048.79 | 26,201.39 |
| | Tot. Reg. 1 | **78,885.64** | **109,911.11** | **84,021.54** | **85,118.83** | **84,190.88** |
| Reg. 2 | A | 26,834.69 | 29,612.42 | 28,745.59 | 29,485.32 | 28,675.66 |
| | B | 26,064.62 | 28,563.08 | 27,351.46 | 28,429.82 | 27,339.13 |
| | C | 26,070.33 | 26,398.86 | 26,369.83 | 26,364.56 | 26,544.42 |
| | Tot. Reg. 2 | **78,969.64** | **84,574.36** | **82,466.87** | **84,279.70** | **82,559.21** |
| | Total | **157,855.29** | **194,485.47 (+23.2%)** | **166,488.42 (+5.5%)** | **169,398.5 (+7.3%)** | **166,750.1 (+5.6%)** |

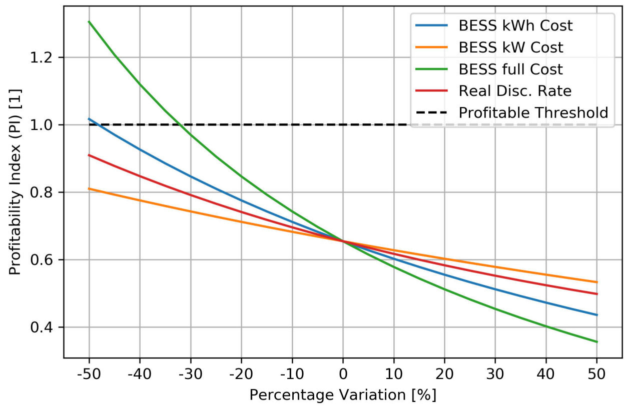



**FIGURE 18. Profitability index as function of variation in BESS capital costs per unit of power, per unit of energy, in power/energy combined, and real discount rate. Mainly a high reduction (below 30%) of the battery's per-unit combined (power + energy) cost would lead to a positive profitability.**

to make grid-scale storage profitable, which would report the highest PI equal to 0.81 and 0.91, respectively.

### B. SENSITIVITY TO BESS SIZE: RATED OUTPUT AND CAPACITY

Sizing BESS is, together with the siting, a key decision in energy storage systems that affects the technical and economic capabilities of the asset. In this subsection, the variation of the profitability index of the project is evaluated attending to different BESS sizes in terms of rated power output and energy capacity. Since the initial size of the battery system was set according to typical values found in the literature, the sensitivity analysis includes 120 variations of the BESS size, 119 cases plus the reference case (i.e. 960 kW and 3,800 kWh evaluated throughout the paper). The size variations are presented for the grid-level BESS in presence of Volt-Var controlled inverters for a PV penetration of 35%, as this is highest maximum hosting capacity in the cases with storage. The power output of the battery's inverter is considered from 0.1 p.u. to 1.5 p.u. at 0.1 steps of the peak demand in the base case (i.e. 1.9 MW). The capacity is considered as the number of hours of operation of the battery from 1 to 8 hours.

Typically, a larger BESS size enables higher technical capabilities. For example, a larger power output rating would allow higher peak power output for load shaving purposes. Similarly, additional capacity to store energy would permit responding to the network needs, such as longer shifts of electricity when performing energy arbitrage or peak load shaving. As a result, the revenue received by a centralised BESS for the provision of services related to real power supply would increase if higher operational rating were available. However, the associated capital cost, which is defined per unit of power or energy, would also raise the initial investment and the operational costs of the storage systems. The effect on the economic profitability of the storage project would then be related to the per unit costs. In other words, what would be higher: the battery's per unit revenue or the per unit cost? This is addressed in this subsection by analysing the economic profitability of the project attending to multiple combinations of power and energy rating.

The effect of the economic profitability of the project as function of the power output and energy capacity ratings is presented in Figure 19. In the range of BESS sizes analysed, the only power output with positive profitability for any battery capacity is 0.1 p.u., where the maximum PI is found at 1 hour of capacity (PI=14.2). In the studied system,

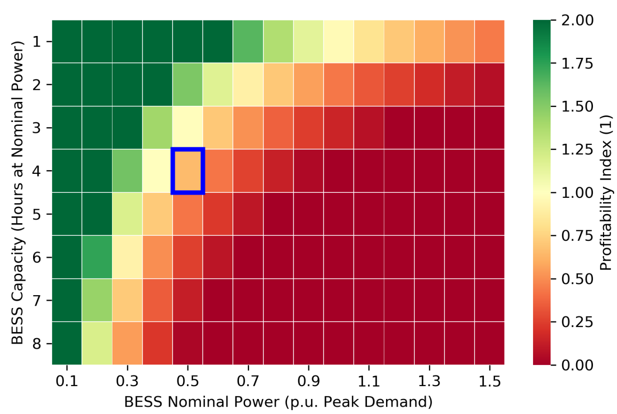



**FIGURE 19. Profitability index as function of the BESS nominal power and capacity for the PV VV + BESS case and a PV penetration of 35% (reference scenario marked). An index higher than 1 would represent a positive profitability.**

a 0.1 p.u. nominal power would correspond to 190 kW. It is however unlikely the deployment of grid-scale BESS with a nominal power rating equal to 190 kW in a MV distribution network, although it could occur in LV networks. Overall, it is possible to observe how the profitability increases with both lower nominal power and lower capacity ratings. From the reference case, reducing the capacity to 2 hours would make the grid-scale BESS profitable (PI=1.52). Similarly, reducing the nominal power to 0.3 p.u. would also make the storage project profitable (PI=1.56). The results suggest that an increase in the nominal power may report higher economic benefits than an increase in the energy capacity. This is probably for the increased cost per unit of energy than per unit of power in BESS technology.

## VII. DISCUSSION

The assessment of grid-scale BESS in presence of distributed PV in the IEEE 34-node system has been carried from a techno-economic perspective throughout the paper to evaluate the role of the grid-scale storage solutions in integrating solar energy. This section discusses the findings and their implications regarding the integration of PV systems using smart inverters and the performance of the grid-scale BESS.

### A. PV INTEGRATION WITH SMART INVERTER CAPABILITIES

Distributed PV in the IEEE 34-node system had multiple smart-control strategies for the dispatch of reactive power by the inverters. Smart-control capabilities in PV inverters are considered to enhance the hosting capacity and contribute to maintain voltage profiles within statutory limits [28]. Constant or fixed power factor using power factor unity, 0.95 inductive and 0.95 capacitive were examined for the maximum PV hosting capacity. The results showed that the power factor can have a significant impact on the hosting capacity limits of a power network. The differences in the hosting capacity of the network reached 10% among cases with stand-alone distributed PV (see Table 10), where the lowest capacity (20%) was found in the case with 0.95 inductive power factor with the remaining 0.95 capacitive and unity power factors equal to 30%. The lower maximum capacity of an inductive power factor can be understood as the injection of real power from the PV can raise the voltage at the point of connection, which can be further raised by the injection of inductive reactive energy.

Besides constant power factor control, PV inverters using Volt-Var control were investigated. Concerning the maximum hosting capacity, the results reported the same limit of 30% PV penetration. However, inverters using Volt-Var control positively contribute to locally supply reactive energy and reducing the demand of reactive energy to the grid. In addition, when grid-scale BESS is present, Volt-Var inverters help enhancing the maximum hosting capacity further than the case with storage and constant power factor control. Volt-Var inverters were also shown to reduce the duty cycles, and in consequence, the economic cost, of in-line voltage regulators in the network when compared to the constant PF mode. It is worth noting that the behaviour of smart inverters with Volt-Var control is conditioned by its location in the network. Thus, the location of the distributed PV in the network is the determinant factor for the dispatch of reactive energy by the inverter as it was illustrated in Figure 12.

Overall, it can be observed that Volt-Var control per se or combined to other smart-control techniques (e.g., Volt-Var combined with Volt-Watt) can be more beneficial to the network than constant, fixed power factor solutions. However, when smart control for PV inverters is not available, unity power factor would be a more adequate choice than any inductive power factor, provided that there were no other network requirements.

### B. TECHNICAL PERFORMANCE OF GRID-LEVEL BESS

The siting decision of energy storage systems was the first of the topics covered in the IEEE 34-node test feeder, where a no-preference, multi-parametric optimisation model was used in order to find a global optimal bus where to allocate the grid-scale BESS. The multiple variables included were both technical and economic parameters of the network and the optimal bus was common in both solutions, with PV using constant PF and Volt-Var control. Nevertheless, the selection of other technical variables, the focus on a different temporal resolution or economic-only parameters would have resulted in different optimal solutions for the grid-scale storage system as illustrated by the results, which is aligned with the conclusions in [59] about the most cost-effective location of BESS considering several technical variables or services. The best ranked bus to allocate front-of-the-meter storage resulted in a location in the main branch and towards the centre of the network, where the bi-directional power flows of distributed PV could be observed by the grid-scale BESS.

The technical evaluation investigated the energy balance of real power, where the results showed a reduction of the network losses compared to the base case when deploying stand-alone PV and PV plus grid-scale storage. The lowest system losses were found for the case with grid-scale storage and PV using Volt-Var at 35% PV penetration (7.46% losses), which represents a reduction by 16.88% compared to the base case. The reduction of electric losses observed from the integration of PV is one of the benefits for the network, which is in alignment with the literature, e.g., [60]. The energy balance of reactive power was also evaluated and it presented considerable changes when introducing grid-scale BESS, which largely reduced the requirements of capacitive/leading reactive energy in the network.

Concerning the maximum PV hosting capacity, the combined deployment of inverters controlled by Volt-Var mode and grid-scale storage enabled a 5% further hosting capacity than the PV Volt-Var mode without storage. Thus, the introduction of grid-scale BESS favours higher PV penetration, which is one of the main benefits often searched in ESS [61], [62]. All the maximum hosting capacities were above 15%, which is the traditional threshold used in industry before require significant interventions in the network [25]; however, the maintenance requirements of electrical infrastructure (e.g., in-line voltage regulator) could be moderately affected with earlier maintenance needed up to 5 years in advance (see Figure 14). Hence, the results of the assessment reinforce the idea that advanced studies for solar PV integration should replace conventional rules-of-thumb [10], [25] and be integrated as part of the early stages of distribution network planning process to enable requests for PV connections.

Regarding the network analysed, the IEEE 34-bus test feeder has its origin in Arizona, USA. The configuration of the network in terms of voltage control (i.e. an in-feed transformer without voltage regulation and this being implemented by in-line voltage regulators in different locations of the network) may not correspond to typical networks found in Northern Ireland and other parts of the UK, where on-load-tap-changing transformers at substation level would be used for voltage regulation. Thus, the technical performance in typical UK-based primary distribution networks (e.g., 33 kV network) may differ to that presented in relation to voltage compensation and other depending features, such as the maximum hosting capacity. Yet, the IEEE 34-node system provides a test bed for the concept of aggregated impact from distributed PV with storage systems at the level of bulk supply points, which is the focus of this paper.

Overall, centralised, front-of-the-meter BESS in distribution-level power networks:

1) reduces the system energy losses;
2) enhances the maximum PV hosting capacity;
3) minimises the requirements of capacitive reactive energy in the network; and
4) helps mitigate the extra operation of near-by grid assets, such as in-line voltage regulators, compared to cases with distributed PV and without storage. The maintenance and replacement costs of in-line voltage regulators increase due to distributed PV, but the additional cost is low to moderate considering the long lifetime of power infrastructure.

### C. ECONOMIC PERFORMANCE OF GRID-LEVEL BESS

The economic assessment provided with a break-down of the revenue streams from real and reactive power supply, where over 98.9% of the revenue came from real power supply. However, the assessment quantifies the revenue from reactive power supply, which is generally omitted in the literature [4]. Overall, the economic metrics illustrate that the grid-level BESS would not be profitable as an asset, primarily driven by the additional cost of the battery replacements throughout the life span of the project. Nonetheless, the deployment of grid-scale BESS in the network with distributed PV helps minimise the interventions of electrical infrastructure, such as that of in-line voltage regulators.

A sensitivity analysis for the profitability of the project was performed based on variations of the size and macro-economic parameters of the grid-scale battery system. The findings suggest that higher battery inverter power output would produce higher benefits than larger energy capacities. The profitability can turn into positive with variations of both energy capacity and nominal output rating. Looking at the evolution of macro-economic variables, a potential high reduction in the battery cost per unit of energy, which would align with the most optimistic scenarios for the long-term future of lithium-ion battery packs [45], would significantly benefit the profitability of grid-scale BESS projects.

#### What would it take for profitable grid-level BESS with a focus on the integration of small-scale distributed PV?

The revenue streams for the supply of real and reactive power were assessed by scaling available services to large generators (e.g., whole-sale electricity supply and reactive energy/voltage compensation), which are typical transmission-level/TSO-based services. The results showed that TSO-based services are not enough for the economic profitability of grid-level BESS acting in distribution networks. Similar findings were found by Brogan *et al.* [23] when analysing the grid-scale BESS for ancillary services, including to fast-frequency response and operating reserves (primary, secondary and tertiary reserve) in the Irish power system. Nonetheless, incorporating and stacking multiple revenue streams can assist the economic profitability of grid-level BESS when the financial viability is marginal.

As a result, distribution network-specific services could be a solution in the future to manage and support the integration of renewable DG locally. Initiatives related to these services are starting to be implemented across Europe but are not currently on-going in the all-island Irish power system. However, a trial project in Northern Ireland commences in the last quarter of 2021 (i.e., the FLEX project [18]). In relation to distribution-specific services by distributed BESS, previous work in the Irish power system by Raouf Mohamed *et al.* [19] showed that economic viability of these projects can be again negative or marginal. To this end, the potential ranges of payment received by generators due to real and reactive energy supply were explored to find the financial break-even limit between positive to negative profitability. The findings show that an annual average payment for real power supply higher than 48.7 GBP/MWh (4.87 p/kWh) or for reactive power supply higher than 28.8 GBP/Mvarh (2.88 p/kvarh) would make profitable the grid-scale BESS project considered. Besides these price thresholds, multiple solutions for the payment received by front-of-the-meter storage systems could be set according to the linear relationship found.

Concurrently, the paper explored a complementary way to enhance the profitability of grid-scale energy storage systems could be by partly or totally account the economic savings that the storage systems produce in the power network. PV integration brings a large economic benefit due to the avoided cost in $CO_2$ emissions trading credits. This benefit is expanded by the integration of grid-scale BESS (see Table 13) due to better management of local PV generation (i.e., higher self-consumption) and extra hosting capacity enabled by the storage systems in the case PV VV + BESS (5% additional PV hosting capacity than with the PV VV case). Thus, any consideration of the economic added value of the grid-scale BESS integrated as part of the project's economics would help the profitability of front-of-the-meter energy storage systems, e.g., as a variable payment mechanism depending on the solar generation in the network. Overall, the implications of this potential profitability for grid-level BESS would be related to the design of new services for the case of distribution-specific compensation.

## VIII. CONCLUSION AND FUTURE WORK

This paper constitutes an exhaustive study that permits drawing conclusions about the cost-effectiveness of grid-level storage systems in presence of stand-alone distributed PV systems in the context of distribution-specific services. The assessment included multiple aspects of energy storage systems, such as: the siting decision of BESS; the technical characteristics of the network; the economic revenue from real and reactive energy supply; the economic effect in the grid infrastructure from decarbonising the network; and PV hosting capacity with smart control strategies for PV inverters.

By covering all these topics on grid-level storage and distributed PV systems simultaneously, and in the same case study, the results illustrated several technical benefits of grid-scale BESS in fostering PV integration: (i) it minimises the real energy supplied by the grid through the substation around 5%, and cuts down by 125% on average the volume of reactive energy (including inductive and capacitive reactive energy); (ii) it reduces the system losses up to 16.88% compared to the base case without PV; and it diminishes the losses 1-3% compared to the cases of PV presence without storage; (iii) it improves the voltage of the network by reducing the maximum voltage levels across the network, which enables further PV hosting capacity by an additional 5% under the presence of Volt-Var controlled inverters; (iv) it helps mitigate the duty cycle of distribution network assets, such as in-line voltage regulators, which permits extending the period scheduled maintenance by half a year, and the lifetime of the devices around 2 years compared to the cases when storage is not present.

Despite the technical benefits, grid-scale BESS projects as the studied were not found economic profitable per se. The cash-flow analysis showed that battery replacements represent large cash withdrawals that affect negatively the profitability of the project, leading to net present values over 350,000 GBP and an internal rate of return of −23.9%. Nevertheless, the paper explored viable compensation rates for distribution-specific services of grid-scale BESS that could make these assets profitable. It was estimated that annual average payments of 48.7 GBP/MWh and of 28.8 GBP/Mvarh would make profitable grid-scale BESS projects as the proposed. Overall, we conclude that the positive economic profitability of large centralised distributed BESS lies in developing distribution-specific services that reflect the local value and flexibility benefits provided. For example, centralised BESS can reduce by 15.9% the cost of in-line voltage regulators during their lifetime when PV systems don't have smart control capabilities, or it can expand the PV hosting capacity without increasing the cost when smart PV inverters are deployed. Moreover, several ideas based on the impact on electrical infrastructure and decarbonisation in the electricity network were assessed to benefit and enhance the profitability of grid-scale BESS. For instance, developing compensation schemes that include the additional avoided cost in CO2 trading credits enabled by centralised BESS could increase the revenue up to 63,000 GBP during the project's lifetime.

As the energy transition continues, distribution network operators will increasingly face new challenges in dealing with local micro-grids and additional services, such as inertial support, and islanding detection, compensation and restoration. It is possible to consider that the transition from distribution network operators into distribution system operators might bring transmission-like services to the distribution network level. To this end, the results of this paper can direct system and market operators, and energy regulators towards developing schemes to incentivise large, centralised BESS in distribution networks in the context of distribution-specific serv. The research community and system operators can also use this study as a reference and benchmark our results in future studies in the available IEEE test feeder. Future research could further analyse planning implications of grid-level storage in distribution networks in the context of micro-grids (e.g., reliability and risk analysis). Future work can also continue exploring distribution-oriented services as a possibility and the design of market and ownership schemes that would allow these practices while ensuring the principles of competence in the electricity markets and the independence of system operators and market participants.

## APPENDIX
## SUPPLEMENTARY MATERIAL

The annual timeseries at 1-minute resolution of the per-unit profiles used for the electric load and the per-unit power output 8 PV systems are available as a supplementary material.

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## REFERENCES

[1] IRENA, "Renewable capacity statistics 2021," Int. Renew. Energy Agency, Abu Dhabi, United Arab Emirates, Tech. Rep., 2021.

[2] S. P. Burger, J. D. Jenkins, C. Batlle, and I. J. Pérez-Arriaga, "Restructuring revisited—Part 1: Competition in electricity distribution systems," *Energy J.*, vol. 40, no. 3, pp. 31–54, Jul. 2019.

[3] F. M. Uriarte, C. Smith, S. Van Broekhoven, and R. E. Hebner, "Microgrid ramp rates and the inertial stability margin," *IEEE Trans. Power Syst.*, vol. 30, no. 6, pp. 3209–3216, Nov. 2015.

[4] J. Lopez Lorente, X. A. Liu, R. Best, and D. J. Morrow, "Energy storage allocation in power networks—A state-of-the-art review," in *Proc. 53rd Int. Universities Power Eng. Conf. (UPEC)*, Sep. 2018, pp. 1–6.
[5] J. McLaren, N. Laws, K. Anderson, N. DiOrio, and H. Miller, "Solar-plus-storage economics: What works where, and why?" *Electr. J.*, vol. 32, no. 1, pp. 28–46, Jan. 2019.
[6] K. Uddin, R. Gough, J. Radcliffe, J. Marco, and P. Jennings, "Techno-economic analysis of the viability of residential photovoltaic systems using lithium-ion batteries for energy storage in the United Kingdom," *Appl. Energy*, vol. 206, pp. 12–21, Nov. 2017.
[7] J. Koskela, A. Rautiainen, and P. Järventausta, "Using electrical energy storage in residential buildings—Sizing of battery and photovoltaic panels based on electricity cost optimization," *Appl. Energy*, vol. 239, pp. 1175–1189, Apr. 2019.
[8] A. Foles, L. Fialho, and M. Collares-Pereira, "Techno-economic evaluation of the Portuguese PV and energy storage residential applications," *Sustain. Energy Technol. Assessments*, vol. 39, Jun. 2020, Art. no. 100686.
[9] R. Boampong and D. P. Brown, "On the benefits of behind-the-meter rooftop solar and energy storage: The importance of retail rate design," *Energy Econ.*, vol. 86, Feb. 2020, Art. no. 104682.
[10] J. P. Carvallo, N. Zhang, S. P. Murphy, B. D. Leibowicz, and P. H. Larsen, "The economic value of a centralized approach to distributed resource investment and operation," *Appl. Energy*, vol. 269, Jul. 2020, Art. no. 115071.
[11] C. A. S. Rangel, L. Canha, M. Sperandio, and R. Severiano, "Methodology for ESS-type selection and optimal energy management in distribution system with DG considering reverse flow limitations and cost penalties," *IET Gener., Transmiss. Distrib.*, vol. 12, no. 5, pp. 1164–1170, 2018.
[12] I. Konstantelos and G. Strbac, "Capacity value of energy storage in distribution networks," *J. Energy Storage*, vol. 18, pp. 389–401, Aug. 2018.
[13] F. R. S. Sevilla, D. Parra, N. Wyrsch, M. K. Patel, F. Kienzle, and P. Korba, "Techno-economic analysis of battery storage and curtailment in a distribution grid with high PV penetration," *J. Energy Storage*, vol. 17, pp. 73–83, Jun. 2018.
[14] A. Valencia, R. A. Hincapie, and R. A. Gallego, "Optimal location, selection, and operation of battery energy storage systems and renewable distributed generation in medium-low voltage distribution networks," *J. Energy Storage*, vol. 34, no. 102158, pp. 1–16, 2021.
[15] M. Zidar, P. S. Georgilakis, N. D. Hatziargyriou, T. Capuder, and D. Škrlec, "Review of energy storage allocation in power distribution networks: Applications, methods and future research," *IET Generat., Transmiss. Distrib.*, vol. 10, no. 3, pp. 645–652, Mar. 2016.
[16] A. Castillo and D. F. Gayme, "Grid-scale energy storage applications in renewable energy integration: A survey," *Energy Convers. Manage.*, vol. 87, pp. 885–894, Nov. 2014.
[17] P. V. Brogan, R. J. Best, D. J. Morrow, K. McKinley, and M. L. Kubik, "Effect of BESS response on frequency and RoCoF during underfrequency transients," *IEEE Trans. Power Syst.*, vol. 34, no. 1, pp. 575–583, Jan. 2019.
[18] *FLEX Project and Procurement of Flexibility Services*, NIE Networks, London, U.K., 2021.
[19] A. A. R. Mohamed, D. J. Morrow, R. J. Best, A. Cupples, I. Bailie, and J. Pollock, "Distributed battery energy storage systems operation framework for grid power levelling in the distribution networks," *IET Smart Grid*, early access, May 2021, doi: 10.1049/stg2.12040.
[20] A. Bagchi, R. Best, D. J. Morrow, J. Pollock, I. Bailie, and A. Cupples, "System service provision capabilities of storage devices connected to a MV distribution network: A northern Ireland case study," in *Proc. IEEE Power Energy Soc. Innov. Smart Grid Technol. Conf. (ISGT)*, Feb. 2020, pp. 1–5.
[21] Y. Zhang, Y. Xu, H. Yang, Z. Y. Dong, and R. Zhang, "Optimal whole-life-cycle planning of battery energy storage for multi-functional services in power systems," *IEEE Trans. Sustain. Energy*, vol. 11, no. 4, pp. 2077–2086, Oct. 2020.
[22] L. Maeyaert, L. Vandevelde, and T. Döring, "Battery storage for ancillary services in smart distribution grids," *J. Energy Storage*, vol. 30, Aug. 2020, Art. no. 101524.
[23] P. V. Brogan, R. Best, J. Morrow, R. Duncan, and M. Kubik, "Stacking battery energy storage revenues with enhanced service provision," *IET Smart Grid*, vol. 3, no. 4, pp. 520–529, Aug. 2020.
[24] N. Singh Rayit, J. I. Chowdhury, and N. Balta-Ozkan, "Techno-economic optimisation of battery storage for grid-level energy services using curtailed energy from wind," *J. Energy Storage*, vol. 39, no. 102641, pp. 1–14, 2021.
[25] B. Palmintier, R. J. Broderick, B. Mather, M. Coddingtom, K. Baker, F. Ding, M. J. Reno, M. Lave, and A. Bharatkumar, "On the path to SunShot: Emerging issues and challenges in integrating solar with the distribution system," Nat. Renew. Energy Lab., Golden, CO, USA, Tech. Rep. NREL/TP-5D00-65331, 2016.
[26] R. Seguin, J. Woyak, D. Costyk, J. Hambrick, and B. Mather, "High-penetration PV integration handbook for distribution engineers," Nat. Renew. Energy Lab., Golden, CO, USA, Tech. Rep. NREL/TP-5D00-63114, 2016.
[27] M. Zeraati, M. E. H. Golshan, and J. M. Guerrero, "Voltage quality improvement in low voltage distribution networks using reactive power capability of single-phase PV inverters," *IEEE Trans. Smart Grid*, vol. 10, no. 5, pp. 5057–5065, Sep. 2019.
[28] J. F. B. Sousa, C. L. T. Borges, and J. Mitra, "PV hosting capacity of LV distribution networks using smart inverters and storage systems: A practical margin," *IET Renew. Power Gener.*, vol. 14, no. 8, pp. 1332–1339, Jun. 2020.
[29] K. Miettinen, "No-preference methods," in *Nonlinear Multiobjective Optimization*. Boston, MA, USA: Springer, 1998, Ch. 3, pp. 67–76.
[30] O. Babacan, W. Torre, and J. Kleissl, "Siting and sizing of distributed energy storage to mitigate voltage impact by solar PV in distribution systems," *Sol. Energy*, vol. 146, pp. 199–208, Apr. 2017.
[31] SMA, "Grid support utility interactive inverters: Technical information sunny boy series," Niestetal, Germany, Tech. Rep. SC_SCS-US-GridServices-TI-en-11, 2015.
[32] Northern Ireland Electricity Networks, "Distribution code: Issue 5–26 April 2019," NIE Netw., Belfast, U.K., 2019.
[33] K. Mongrid, V. Viswanathan, P. Balducci, J. Alam, V. Fotedar, V. Koritarov, and B. Hadjerioua, "Energy storage technology and cost characterization report," Pacific North-West Lab., US DoE, Richland, WA, USA, Tech. Rep. PNNL-28866, 2019.
[34] Operation Directorate ENA, "Engineering recommendation G99/NI," ENA, Energy Netw. Assoc., UK and Ireland, London, U.K., 2019.
[35] W. H. Kersting, "Radial distribution test feeders," in *Proc. IEEE Power Eng. Soc. Winter Meeting. Conf.*, Feb. 2001, pp. 908–912.
[36] K. P. Schneider, B. A. Mather, B. C. Pal, C. W. Ten, G. J. Shirek, H. Zhu, J. C. Fuller, J. L. R. Pereira, F. L. Ochoa, L. R. de Araujo, R. C. Dugan, S. Matthias, S. Paudyal, T. E. McDermott, and W. H. Kersting, "Analytic considerations and design basis for the IEEE distribution test feeders," *IEEE Trans. Power Syst.*, vol. 33, no. 3, pp. 3181–3188, Oct. 2017.
[37] IEEE PES AMPS DSAS Test Feeder Working Group, "IEEE test feeder cases," IEEE, Feb. 2016. Accessed: Aug. 1, 2021. [Online]. Available: https://cmte.ieee.org/pes-testfeeders/resources/
[38] ELEXON, *Load Profiling*, ELEXON Ltd., Oct. 2018. Accessed: Aug. 1, 2021. [Online]. Available: https://www.elexon.co.uk/operations-settlement/profiling/
[39] *EPRI Open Source Distribution System Simulator, OpenDSS*, Electric Power Research Institute (EPRI), Washington, DC, USA, 2008.
[40] *The Copernicus Atmosphere Monitoring Service (CAMS) All-Sky Radiation Service*, European Centre for Medium Range Forecasting, Reading, U.K., 2020.
[41] T. Huld, G. Friesen, A. Skoczek, R. P. Kenny, T. Sample, M. Field, and E. D. Dunlop, "A power-rating model for crystalline silicon PV modules," *Sol. Energy Mater. Sol. Cells*, vol. 95, no. 12, pp. 3359–3369, Dec. 2011.
[42] D. Faiman, "Assessing the outdoor operating temperature of photovoltaic modules," *Prog. Photovolt., Res. Appl.*, vol. 16, no. 4, pp. 307–315, Jun. 2008.
[43] M. R. Clayman, *Corporate Finance: A Practical Approach*, 2nd ed. Hoboken, NJ, USA: Wiley, 2012.
[44] Contracts and Settlement Department SONI, "Transmission use of system: Statement of charges," Electr. Syst. Operator Northern Ireland, Belfast, U.K., Tech. Rep., 2019.
[45] *Battery Pack Prices Fall as Market Ramps up With Market Average at $156/kWh in 2019*, Bloomberg New Energy Finance, New York, NY, USA, 2019.
[46] IRENA, "Electricity storage and renewables: Costs and markets to 2030," Int. Renewable Energy Agency, Abu Dhabi, United Arab Emirates, Tech. Rep., Oct. 2017.
[47] *Lazard's Levelized Cost of Storage Analysis Version 4.0*, Lazard, New Orleans, LA, USA, 2018.
[48] Northern Ireland Electricity Networks, "Statement of charges for connection to Northern Ireland electricity networks' distribution system (Version 1.2)," NIE Netw., Belfast, U.K., 2020.
[49] *System Advisor Model Version 2018.11.11 (SAM 2018.11.11)*, Nat. Renew. Energy Lab. [Online]. Available: https://sam.nrel.gov/

[50] J. Simon and G. Mosey, "Feasibility study of economics and performance of solar photovoltaics at the VAG mine site in Eden and Lowell, Vermont. A study prepared in partnership with the environmental protection agency for the RE-powering America's land initiative," Nat. Renew. Energy Lab., Golden, CO, USA, Tech. Rep. NREL/TP-7A30-57766, 2013.
[51] Monetary Policy Committee, "Monetary policy report—August 2020," Bank England, London, U.K., Tech. Rep., 2020.
[52] A. Obusevs, R. Knecht, F. Carigiet, F. Baumgartner, and P. Korba, "Sol: Cost effective smart grid solutions for the integration renewable power sources into the low-voltage networks (final report)," Swiss Federal Ofce Energy, Bern, Switzerland, Final Rep., 2019.
[53] J. Bian, X. Sun, M. Wang, H. Zheng, and H. Xing, "Probabilistic analysis of life cycle cost for power transformer," *J. Power Energy Eng.*, vol. 2, no. 4, pp. 489–494, 2014.
[54] D. Dohnal, "MR knowledge base: On-load tap-changers for power transformers (F0126405)," Maschinenfabrik Reinhausen GmbH, Regensburg, Germany, Tech. Rep. F0126405, 2013.
[55] V. Hatherick, "EU ETS price 32-65/t under 2030 scenarios," Argus Emissions Resour., Sep. 2020. Accessed: Aug. 1, 2021. [Online]. Available: https://www.argusmedia.com/en/news/2142240-eu-ets-price-3265t-under-2030-scenarios
[56] DAERA Northern Ireland, "Northern Ireland carbon intensity indicators 2020," DAERA, Dept. Agricult., Environ. Rural Affairs Northern Ireland, Belfast, U.K., Tech. Rep. DMS 20.21.087, 2020.
[57] *Market Data Day-Ahead Market Price, Single Electricity Market Operator of Ireland (SEMO)*, Single Electricity Market Operator, Mar. 2020. Accessed: Jan. 15, 2021. [Online]. Available: https://www.sem-o.com/market-data/
[58] EirGrid Group, "DS3 system services statement of payments," Irish Electr. Transmiss. Syst. Operator, EirGrid, Dublin, Ireland, Tech. Rep., 2018.
[59] N. Jayasekara, M. A. S. Masoum, and P. J. Wolfs, "Optimal operation of distributed energy storage systems to improve distribution network load and generation hosting capability," *IEEE Trans. Sustain. Energy*, vol. 7, no. 1, pp. 250–261, Jan. 2016.
[60] K. K. Mehmood, S. U. Khan, S. Lee, Z. M. Haider, M. K. Rafique, and C. Kim, "Optimal sizing and allocation of battery energy storage systems with wind and solar power DGs in a distribution network for voltage regulation considering the lifespan of batteries," *IET Renew. Power Gener.*, vol. 11, no. 10, pp. 1305–1315, Aug. 2017.
[61] R. Fernández-Blanco, Y. Dvorkin, B. Xu, Y. Wang, and D. S. Kirschen, "Optimal energy storage siting and sizing: A WECC case study," *IEEE Trans. Sustain. Energy*, vol. 8, no. 3, pp. 733–743, Jul. 2016.
[62] P. Denholm and T. Mai, "Timescales of energy storage needed for reducing renewable energy curtailment," *Renew. Energy*, vol. 130, pp. 388–399, Jan. 2019.

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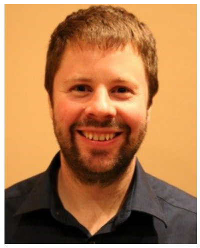

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