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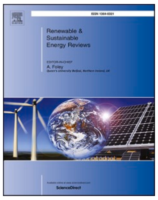

Techno-environmental analysis of battery storage for grid level energy services

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ABSTRACT

With more and more renewable energy sources (RES) going into power grids, the balancing of supply and demand during peak times will be a growing challenge due to the inherent intermittency and unpredictable nature of RES. Grid level batteries can store energy when there is excess generation from wind and solar and discharge it to meet variable peak demand that is traditionally supplied by combined cycle gas turbine (CCGT) plants. This paper assesses the potential of battery storage to replace CCGT in responding to variable peak demand for current and future energy scenarios (FES) in the UK from technical and environmental perspectives. Results from technical analysis show that batteries, assuming size is optimised for different supply and demand scenarios proposed by the National Grid, are able to supply 6.04%, 13.5% and 29.1% of the total variable peak demand in 2016, 2020 and 2035, respectively while CCGT plants supply the rest of the demand. Particularly, to phase out CCGT variable generation from the UK grid in 2035, electricity supply from wind and solar needs to increase by 1.33 times their predicted supply in National Grid's FES. The environmental implications of replacing CCGT by batteries are studied and compared through a simplified life cycle assessment (LCA). Results from LCA studies show that if batteries are used in place of CCGT, it can reduce up to 87% of greenhouse gas emissions and that is an estimated 1.98 $MtCO_2$ eq. for an optimal supply, 29.1%, of variable peak demand in 2035.

1. Introduction

Electricity and heat generation accounts for 25% of global greenhouse gas (GHG) emissions [1]. The Paris Agreement negotiated in 2015 aims to limit global warming to less than 2 °C above the pre-industrial level to significantly reduce the risks and impacts associated with climate change [2]. According to the 2008 Climate Change Act, the UK has a long-term domestic goal of reducing greenhouse gas emissions by 80% from 1990 levels by 2050, which was recently updated to net-zero emission target. To achieve this target, the UK should reduce its emissions by at least 3% annually, and it needs to reach 51% of its emissions reduction target by 2025 [3]. In 2016, 54% of the total electricity generation (336 TWh) in the UK came from fossil fuels, 25% from renewable energy sources (RES) and 21% was sourced from nuclear power [4]. More specifically, electricity supply from combined cycle gas turbine (CCGT) power plants represented around 42% of total supply in the same year [4]. Due to flexibility of operation, around a half of this supply covers variable peak demand throughout a day. However, emissions from CCGT and other fossil fuel sources are very high compared to RES [5]. Therefore, the emission reduction target will have to be achieved by increasing supply from non-fossil fuel sources (e.g. nuclear and RES) [6–8]. The nuclear option, however, has more limitations such as scale-up and waste disposal problems and the challenges to deliver flexibility to follow the load [9]. In contrast, RES, e.g. wind and solar, have limited challenges with waste disposal and environmental pollution, but create other operational issues such as non-programmability and mismatch in supply and demand. In spite of these challenges, the projected generation of UK RES will increase from 101 TWh in 2017 to 192 TWh in 2035 by accounting for 52% of the UK's total electricity generation [6]. On the other hand, during the same period, the generation of fossil fuels, mainly from combined cycle gas turbine (CCGT) and coal plants, is estimated to decrease from 165 TWh to 49 TWh (13% of total electricity generation by 2035) [6]. With this new energy mix, the UK power grid requires substantial dispatchable assets, such as energy storage, to handle unpredictable energy variations

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Nomenclature

Abbreviations

BESS	Battery energy storage system
CCGT	Combined cycle gas turbine
CE	Curtail energy
DO	Demand offset
DOD	Depth of discharge
EES	Electrical energy storage
EP	Excess power
ED	Excess demand
ELCD	European reference life cycle database
FES	Future energy scenarios
GHG	Greenhouse gas
LCA	Life cycle assessment
LCI	Life cycle inventory
RES	Renewable energy sources
TSO	Transmission systems operator

from non-programmable RES.

Electricity cannot be stored directly. It must be converted to another form of energy if it is to be stored. As a result, national electricity supply and demand is balanced on an instantaneous basis by the UK Transmission Systems Operator (TSO), National Grid [10]. This balancing act becomes more challenging and costly with the increase of wind and solar generation due to their intermittent, variable and non-programmable nature. Both solar and wind can be curtailed if there is excess generation but curtailment would become unnecessary with integrating sufficient electrical energy storage (EES) options such as pumped hydroelectric and batteries [9]. In such a case EES in national power system can decouple the timing of RES generation and peak electricity demand, in order to capture the energy generated at a particular time and use it later [11]. This decoupling allows the peak variable load to be supplied from low cost wind and solar and EES, thereby reducing the need to run expensive peak load power generation plants [12]. However, without EES the grid must have standby generation capacity to meet variable peak demand. Even though standby generators may not be used or are occasionally fed back to the grid, both transmission and distribution lines must be sized according to overall generation capacity, creating additional costs for the maintenance of the grid [13]. By implementing EES, the cost of additional transmission lines and backup power plants can be reduced [14].

EES can be divided into two categories based on storage capacity: utility scale using small-scale (typically kW to small MW range) distributed storage including commercial, industrial and residential level; and grid-scale bulk storage ranging from tens to hundreds of MW [15]. Overall, EES offers many services, including micro-grid balancing [16,17], residential and industrial load peak shaving, and power quality management [15] at the utility scale level; and voltage and frequency regulations, reduction of transmission losses, improvement of system reliability, peak load management, grid stabilisation, electrical supply capacity and enhancing renewable integration [18] at the grid level. In general, EES can be applied to energy and power service applications. The term "energy applications" is defined as the continuous supply of energy from EES to services such as load shifting and peak shaving for a period of hours, while "power applications" refers to the use of EES for short term energy supply, usually for seconds or minutes, for various ancillary services such as frequency response and variable renewable generation smoothening [19]. EES technology in energy applications for the grid need to store more energy (MWh) than its power capability (MW), whereas higher power ratings (MW) than energy storage capacity or ratings are required for short time power applications [19].

Most of the literature reviewed on the EES describes the benefits of incorporating more storage into power systems to support more intermittent renewable energy sources [9,20–23]. A recent review of the state of the art in EES notes that there are a wide variety of storage options with complex arrays of business features and specifications, making it difficult to determine which option is suitable for a particular application [24,25]. Historically, due to low construction costs, long life cycle (about 40 years or more), and relatively high round-trip efficiency (up to 75%), most EES applications at grid level have been dominated by pumped hydroelectric storage (PHS) [13]. Recently, compressed air energy storage (CAES) has also proved to be a potential means of storage for grid applications. However, a limitation of both PHS and CAES is the strict requirement for geographical features and suitable locations [26]. On the other hand, battery energy storage system (BESS) provides location flexibility as it can be installed across all levels, from energy generation, transmission, and distribution to consumer level [27]. Furthermore, fast response, modularity, scalability, high efficiency and low maintenance requirements make BESS more suitable for grid-scale bulk-storage applications [26]. Whilst the grid-scale BESS are already competitive for ancillary services such as frequency responses [28,29], peak load shaving [30], load regulation and spinning reserves [31], the same batteries can be scaled up and be used for energy services such as multi-hour energy supply and load shifting [24,32–34].

In the US, China and Germany, a number of BESS projects have been successfully installed and operated for many years. Those BESS projects have power ratings as low as 4 MW up to 36 MW and energy ratings from 10 to 40 MWh, and have been used for wind integration and grid level services [18,35]. In the UK, several BESS projects are either in operation or have been announced to be installed for mainly ancillary services, and their nominal capacity ranges from hundreds of kW to tens of MW [36]. These implementation cases suggest that although BESS has been successfully implemented in small-scale applications, no large-scale energy applications have been implemented so far at grid level anywhere in the world that enables many hours of electricity supply. The reasons for this are the high investment cost and poor and/or uncertain return of investment compared with alternatives such as demand side response and thermal generations [18,19], the lack of large-scale trials for validity and safety, of equitable regulatory environment and of interest by the industry [37] and the absence of market and policy frameworks [38]. Although the business case for grid level energy services might not be attractive at this moment due to the high cost of BESS and other issues, the future prospect is undoubtedly bright with the forecast of low cost batteries [39,40].

In recent years BESS, mainly Sodium-sulphur (Na–S) and Lithium-ion (Li-ion), have seen a growth in installations [18]. Other battery technologies such as Vanadium Redox Batteries (VRB) show promising performance [41]. It was estimated that the life time of VRB is much longer than Li-ion batteries [41]. Nevertheless, VRB are currently under development and it costs around two to three times more than Li-ion batteries [42]. On the other hand, although the Na–S battery is the dominating BESS that is commercially available for grid applications, high operating temperature (300-340 °C) and high self-discharge properties can degrade battery performance [26]. In contrast, the Li-ion battery is considered as a promising BEES option, offering high energy density, high output voltage, high round-trip efficiency, high specific energy and power, and is better than all other batteries currently available in the market [41–43]. Despite these benefits, the success of the Li-ion BESS for grid level applications will depend on how well the battery meets key expectations such as low capital cost, longer lifetime, high durability and reliability [13]. More recently, FLUENCE energy storage company (http://fluenceenergy.com) has launched grid-scale Li-ion BESS to substitute peak power plants, e.g. CCGT. The modular BESS they provide to their customers can be scaled up from 2 MW to over 100 MW with an energy supply capacity from 30 min up to 8 h [44,45]. This could be used to supply variable load during peak times such as in the UK to reduce or replace the power generation demand from CCGT plants. To determine the amount of variable peak demand that can be supplied by renewable powered BESS, sizing and optimisation of storage, considering the whole grid supply and demand scenario, needs to be assessed. Some studies have examined the sizing of energy storage for grid-level peak demand management, but they are restricted to investigation into the potential replacement of an existing fossil-fuel based grid with 100% RES [46] or storage sizing and demand management for a fully renewable grid [47,48]. Especially, the analysis in Ref. [46] argued that two thirds of coal generation from Alberta electricity grid could be replaced by renewables but that would require a large size of battery (350MW/350 MWh) and gas power plants as backup sources to meet peak demands. However, the objective of the study in Ref. [46] was to replace coal generations rather than CCGT which needs further consideration as the latter supplies both the base and variable peak load at the grid. Moreover, the BESS size can vary depending on the supply from RES and CCGT variable generation, which are subject to temporal variation over a year. Hence, it is necessary to consider daily supply and demand data (at high granularity e.g. 5 min intervals) to determine the size of BESS to replace CCGT variable supply in current and future energy scenarios. Additionally, the environmental benefits of replacing CCGT with BESS for variable peak demand management needs to be considered, which has not been studied fully yet. Although there are a few studies [49,50] that are focused on the environmental benefits of a large-scale BESS (e.g. 5MW/5 MWh) for grid use in place of fossil fuel based power plants in Germany, their uses are limited to primary control of a grid, rather than managing peak demands. Also, those studies considered a BESS that was meant to be charged by the electricity from the grid, which cannot guarantee a low carbon BESS solution for the grid unless the grid-mix itself is carbon neutral. Therefore, this study focuses on the UK's specific electricity generation and demand profiles and investigates the need for batteries, which store excess electricity from renewable sources, to offset CCGT variable generation and their potential environmental benefits.

The aim of this study are: i) to determine the amount of variable peak demand that can be supplied by renewable energy powered battery storage based on current supply and demand and in the future for the UK, ii) to analyse the amount of RES generation and storage needed to phase out programmable gas power generation during periods of peak demand, and iii) to assess the environmental implications of replacing CCGT with batteries through life cycle assessments (LCA) of both technologies. The contribution of the paper is to optimise the size of battery storage needed to cover some or all peak variable electricity demand of the UK grid, which otherwise would come from CCGT, and compare environmental benefits of using batteries instead of CCGT. The analysis is extended to cover future electricity generation and consumption scenarios in the UK.

The rest of the paper is organised as follows: Section 2 describes the methodology including data and assumptions, modelling of BESS and LCA of battery and CCGT; Section 3 presents results and comprehensive discussions in light of the UK's current and future energy scenarios; Section 4 derives conclusions and recommends guidelines for future research.

2. Methodology

Historically, peak demand in the UK has been met by conventional and dispatchable power plants such as CCGT plants. CCGT in the UK supplies both baseload electricity with fixed output and peak load electricity with variable output (see Fig. 1). The variable output of such power plants depends on the seasons and time of day and varies with the demand at the grid level. Due to low capacity factor, the running cost of peak plants is very high compared to baseload plants. Besides, the emissions from CCGT is much higher than RES, as discussed in the previous section. With the increase of RES, mainly wind and solar, grid level BESS can play a significant role to integrate more renewables and supply some or all variable peak demand. BESS can store energy when there is excess generation from wind and solar and can discharge the energy to the grid when demand is high. Based on this strategy, it is proposed that the peak variable demand of the grid will be met by the combination of RES (wind and solar) and BESS, instead of CCGT alone. Although CCGT plants deliver baseload and peak variable load of the grid, they can also be used for grid balancing due to fast start-up and regulation capabilities, and as a reserve power and voltage management services [51,52]. It was assumed that both CCGT peak generators and BESS can provide a variety of energy and ancillary services.

2.1. Electricity supply and demand management

The historical data of electricity demand and generation from the UK grid was utilised to calculate the daily base load and daily peak demand. The daily baseload was set at the minimum load point in each 24-h

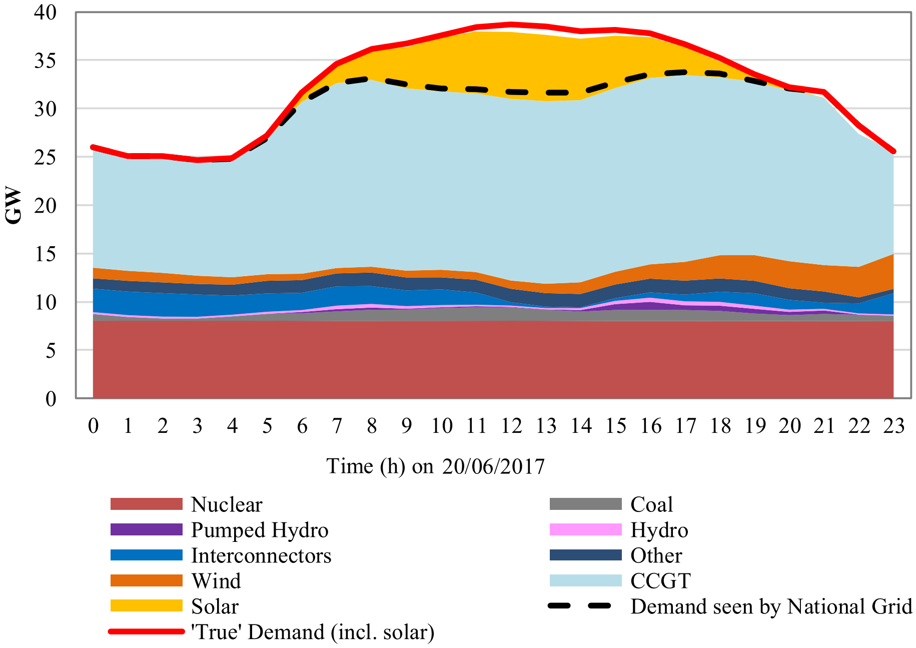

Fig. 1. UK electricity supply and demand profile (hourly basis) on 20/06/2016 at grid level.

period beginning at midnight. The base-load power is provided by large-scale plants that operate on a 24/7 basis and are generally nuclear, coal, CCGT and hydro. In the UK, coal generation was planned to be phased out by 2025 in order to reduce the carbon intensity of electricity generation. The remaining coal fired plants are reaching end-of-life, and they are inefficient by today's standards and costly to maintain with current air quality regulations [53]. Once coal based power plants are phased out, the lost baseload generation capacity will be filled by other existing baseload plants such as nuclear and gas [7]. For the purposes of the study, the base load generators were extended to include biomass as the power generation of the biomass plants are programmable and relatively stable compared to other renewables such as wind and solar. The difference between the daily load curve and baseload is the daily peak demand, which is variable in nature. Most of the peak demand in the UK generation mix is met by the CCGT plants due to its flexibility to increase and decrease the generation capacity [10]. A significant portion is also met by wind and solar, and a small portion from pumped hydro. In this study, it was assumed that non programmable sources, wind and solar, would exclusively be used to meet the variable peak demand or stored in BESS devices. The stored energy during the period of low demand would be used during the time when demand is high, e.g. peak period. The pumped hydro which is a programmable generator would run during the peak demand only, in line with the usual practices (see Fig. 1). The rest of the peak demand would have to be supplied by CCGT-an assumption made in this study. These methodological assumptions are demonstrated in Fig. 2.

2.2. BESS model

The battery considered in this paper is lithium-manganese with a capacity of 5MW/5 MWh. The selected battery manufactured by WEMAG is currently being used for utility scale balancing support in Germany [35,54]. It was assumed that the same battery can be scaled up and located near the wind and solar firms to provide grid level energy services. The aggregate size requirement of the grid level storage was modelled in MATLAB environment, using the UK's national generation and demand dataset, as follows.

Based on the generation and national demand the power mismatch can be calculated as in Eq. (1).

$$\Delta W(t) = G(t) - L(t) \tag{1}$$

where $\Delta W(t)$ is the power mismatch at time t, $G(t)$ is the total generation at time t, and $L(t)$ is the national demand at time t.

Electricity generation at time t is the sum of baseload, wind, solar, pumped hydro and peak portion of CCGT generation. Therefore it can be written as Eq. (2).

$$G(t) = G(t)_{base} + G_{wind}(t) + G_{solar}(t) + G_{PH}(t) + CCGT_{peak}(t) \tag{2}$$

The intention of the system operator is to equalise supply and demand at grid level. However, in most of the cases this is not possible due to unpredictable demand and, crucially, highly variable and non-programmable generation from RES, unless there is a curtailment of supply from wind and solar. Without curtailment, the power mismatch $\Delta W(t)$ can be either positive or negative. When $\Delta W(t)$ is positive, the grid has excess power (EP) to store, and when negative, there is a need for extra supply to meet the excess demand (ED).

Under the supply and demand assumptions mentioned earlier, the excess energy would always be stored in batteries with no constraint of size, e.g. they will be infinitely large enough to store available generation. Once the demand is high and there is less supply, the stored energy would be discharged into the grid. The charge and discharge of the BESS can be modelled as Eq. (3) [47]:

$$BS(t) = BS(t-1) + \begin{cases} \eta_c \Delta W(t) & \text{if } \Delta W(t) \geq 0 \\ \eta_d^{-1} \Delta W(t) & \text{if } \Delta W(t) < 0 \end{cases} \tag{3}$$

where $BS(t)$ is the charging level of infinitely large battery at time t, $BS(t-1)$ is the previous level, η_c is the charging efficiency, η_d is the discharging efficiency.

The efficiency of grid-scale electricity energy storage can vary depending upon the types and size of storage [26]. The lithium-ion (Li-ion) batteries has efficiency ranges from 65% to 98% [21,26,35,55]. The charging and discharging efficiency of the battery is assumed to be 85%, which gives a round trip efficiency of 72.5% [35]. Using batteries as a generating device, the total generation at the grid in Eq. (2) can be re-written as Eq. (4).

$$G(t) = G(t)_{base} + G_{wind}(t) + G_{solar}(t) + G_{PH}(t) + G_{BESS}(t) + CCGT_{peak}(t) \tag{4}$$

Since wind and solar generation were exclusively dedicated to supply the variable load during the periods of peak demand or to charge the BESS devices during the low demand time, the storage capacity is therefore a function of the RES generation and national demand during the period of low demand. The more excess generation there is from wind and solar means the more energy to store in batteries. Once the model in Eq. (3) is run over a period of time, the maximum storage capacity requirement can be calculated based on the maximum and minimum filling levels of the infinitely large storage with Eq. (5).

$$BS_{\max,\inf} = \max[BS(t)] - \min[BS(t)] \tag{5}$$

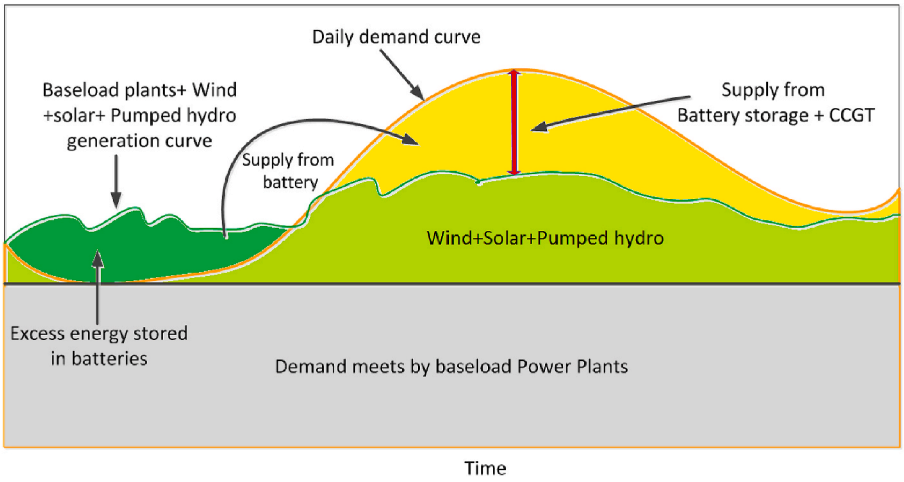

Fig. 2. Electricity supply and demand management under this study.

The maximum size of the infinitely large storage calculated in Eq. (5) works well where the average excess energy available to store in batteries with losses is equal to or less than the average excess demand at the grid. If the opposite is true then the batteries' storage filling level will drift in time by storing more energy than is required to discharge to meet the demand at the grid [47]. In such a situation the selection of maximum storage size using Eq. (5) is not realistic. Therefore the storage size for a case where average excess generation is higher than the average excess demand can be determined using the Eq. (6) [47].

$$BS_{\max,\text{fin}} = \max_{t}\left[BS(t) - \min_{t'>t} BS(t')\right] \tag{6}$$

where$BS(t)$ is the storage filling level of infinitely large storage at time t, $BS(t')$is the storage filling level at time $t'(t'>t)$. The difference between $BS(t)$ and $\min BS(t')$ is the instantaneous storage level at time t. The maximum size of the finite storage can therefore be calculated by taking the highest value of the instantaneous storage level of all times in the model. This way, the storage will not drift in time and be able to store energy to an amount that is required to be discharged during the time of high demand.

The battery size calculated in Eqs. (5) and (6) does not include any restriction for depth of discharge (DOD), so that so the battery can be discharged to its 100% capacity. However, in actual practice 100% DOD will not occur to preserve the life span of the battery. Hence, a DOD,ω, of 90% was assumed in this research [42]. To compensate the DOD limitation, the size of the BESS was adjusted as follows:

$$BS_{\max} = \left(1 + \frac{(1-\omega)}{\eta_d}\right) \times BS_{\max(\text{inf}\quad\text{or}\quad\text{fin})} \tag{7}$$

Additionally, the size adjustment due to battery degradation needs to be considered. All batteries degrade over their life-time due to ageing and charging and discharging cycles. Typically, end-of-life is defined when the battery degrades to a point where only 70–80% of beginning of life capacity is remaining under nameplate conditions [56]. The performance deterioration of WEMAG batteries are expected to be 20% in their lifetime [35,54]. Assuming the degradation of capacity throughout the life, the required battery capacity at the beginning-of-life needs a buffer to account for that impact. Otherwise, the battery could only work fine for a short time before its capacity starts to degrade and could no longer satisfy the needs. Therefore, in practice, the size of BESS would be larger than the size calculated in Eq. (7). In this research, we assumed that the actual size would be 10% higher than the size in Eq. (7), which is supported in the literature [35]. That means the BESS with buffer size will be able to supply the same amount of electricity (average) in each year of its lifetime by over-producing at the beginning of life and under-producing at the end-of-life time.

The overall algorithm flow chart for charging and discharging the infinitely large BESS is shown in Fig. 3(a). Since the battery has no finite limit at this point, the maximum filling level can be infinitely large as well. However, the maximum discharge level is restricted to the current state of charge of batteries. Once the device is charged and demand exceeds supply, the model allows the battery to discharge, thus fulfilling some or all of the excess demand, depending on the conditions. The model at this stage provides the maximum capacity requirement of the BESS and calculates the amount of demand supplied, curtailed energy and required CCGT supply as shown in Fig. 3(a). The estimated maximum storage capacity (for both infinite and finite size) provides the highest excess demand possible for an operating period leading to offsetting maximum amount of CCGT supply. However, this highest demand offset might not be optimal as electricity storage corresponding to

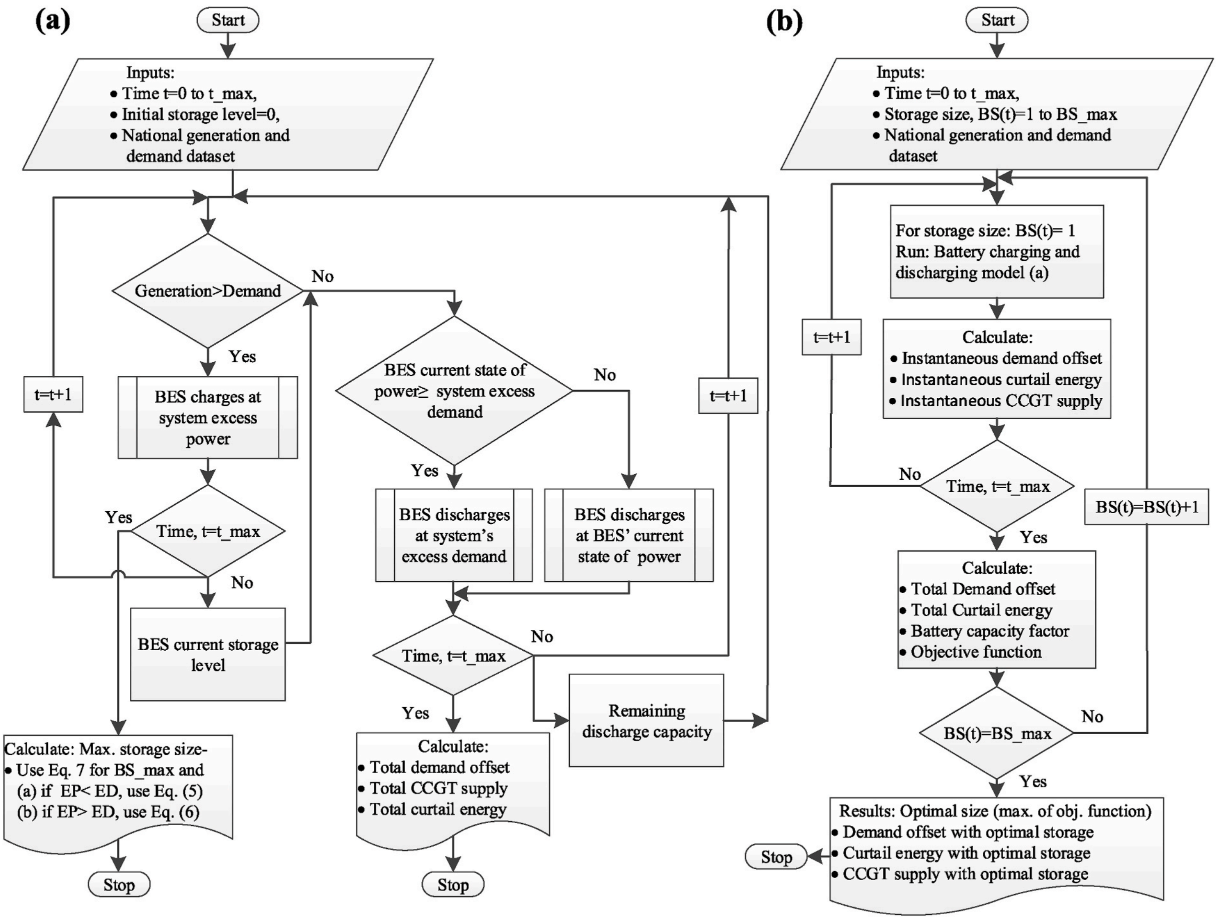

Fig. 3. (a) Charging and discharging algorithm flow chart of BESS model, (b) Optimisation algorithm for BESS.

this capacity will not be discharged every day due to mismatches of supply and demand, and therefore the capacity factor of BESS will be reduced. An algorithm (see Fig. 3(b)) to find the optimal storage size was thus developed and run for storage sizes starting from zero to the maximum as calculated by the algorithm in Fig. 3(a). In this optimisation algorithm the maximum charging and discharging capacity are restricted by Eq. (8).

$$BS(t) = \begin{bmatrix} \min\{(BS(t-1) + \Delta W(t) \times \eta_c),\ \ BS_{\max}\},\ \text{ for charging} \\ \max\{(BS(t-1) + \Delta W(t)/\eta_c),\ \ BS_{\max} \times (1-\omega)\},\ \text{ for discharging} \end{bmatrix} \tag{8}$$

The algorithm shown in Fig. 3(b) calculates demand offset $DO(t)$ by BESS, curtail energy of RES $CE(t)$, CCGT supply $CCGT(t)$ for each time step. The total of these variables and capacity factor cf of batteries for each step increase of the size ΔBS can be calculated in (9)–(12).

$$CE_{total}(\Delta BS) = \sum_{t=0}^{t=n} [\Delta W(t) - \min\{(BS(t-1) + \Delta W(t) \times \eta_c),\ \ BS_{\max}\}],\ \ \Delta W(t) > 0 \tag{9}$$

$$DO_{total}(\Delta BS) = \sum_{t=0}^{t=n} [\max\{(BS(t-1) + \Delta W(t)\ /\ \eta_c),\quad BS_{\min}\}],\quad \Delta W(t) < 0 \tag{10}$$

$$CCGT_{total}(\Delta BS) = \sum_{t=0}^{t=n} [\Delta W(t) - \max\{(BS(t-1) + \Delta W(t)\ /\ \eta_c),\quad BS_{\min}\}],\quad \Delta W(t) < 0 \tag{11}$$

$$cf(\Delta BS) = \frac{DO_{total}(\Delta BS)}{BS_{\max}(\Delta BS) \times t_{total}} \tag{12}$$

The objective function in Eq. (13) to select the optimal size of batteries based on a compromise choice between total demand offset and battery capacity factor is employed in this paper. The global maximum of this objective function represents the optimal size of battery.

$$\text{objective func.} = \max_{\Delta BS = 1,\ \ BS_{\max}} [cf(\Delta BS) \times DO_{total}(\Delta BS)] \tag{13}$$

2.3. Scenario assumptions and data source

The method described in the previous section to determine the size of BESS, which is charged by wind-solar mix, to offset CCGT variable peak generation was applied to UK electricity supply and demand scenarios. The study includes the base year of the analysis, 2016/2017 (referred to as '2016') and the future scenarios in 2020/2021 ('2020') and 2035/2036 ('2035').

Data for base year 2016 was collected from www.gridwatch.co.uk, a website that collects real-time data via the Elexon Portal Balancing Mechanism (BM) Report at 5 min intervals, which comes directly from UK National Grid databases [57]. The base year data reflects a full year's electricity generation portfolio for the UK, and also that a year's worth of weather and seasonal fluctuation of demand. The generation data includes all major power generation plants such as nuclear, CCGT, wind and solar, and interconnectors, etc. The solar data, however, is not recorded centrally by the UK grid due to lack of available information. The data for solar generation is provided by the Sheffield Solar group based in the University of Sheffield [58]. Total solar generation for the UK is estimated using live data from up to 1600 photovoltaic (PV) systems and historical data for over 25,000 systems [58]. In order to ensure the maximum geographical representation relative to real PV systems that are active, Sheffield Solar samples a subset of available systems. On the other hand, the UK hourly national electricity demand figure, as reported by National Grid, is not fully representative of the true scale of electricity demand [57]. This is because the published figure for demand does not include unmetered or embedded generation sources such as solar PV and small-scale unmetered wind generation. This can be seen in Fig. 1 where UK national demand is represented by the black dashed line, but solar generation provides supply for the midday peak in demand, represented by the red line. Thus, in order to account for 'true' demand, solar generation data was added to the electricity demand figure published by the National Grid to reflect the UK demand profile more accurately. Small-scale embedded unmetered wind was disregarded for the purposes of this research as historical data was not readily available.

Interconnectors, for which the UK is a net importer at this moment, contribute around 4.5% in the supply of UK electricity [59]. However, in 2035 the UK will be a net exporter via interconnectors, as predicted by the National Grid's future energy scenarios (FES) [59]. Even though the UK are expected to become a net exporter of power, there will still be imports of electricity that could play crucial roles in the grid such as to provide flexibility services, to charge BESS for energy arbitrage, etc. However, in this research, we aim to charge the BESS with excess electricity from wind and solar rather than other sources such as the interconnector's power, and discharge to the grid for multi-hour energy application, instead of using it for flexibility or energy arbitrage reasons. Given this expectation, for this study it was assumed that the current UK generation (base load plants) was increased to cover the amount of electricity which otherwise would come from interconnectors. Thus, the effect of interconnectors in supply and demand management was excluded in this study.

Recent analysis from the National Grid proposed four different FES until 2050: two degrees, slow progression, steady state and consumer power based on "green ambition" and "prosperity" index of the country [59]. Green ambition is sub-divided as less focused and more focused, whereas the prosperity is split by availability of money - less money and more money. The two degrees scenario is the most ambitious scenario that considers every aspect of political, policy, economic growth rate, social support, technology and environmental policy supports ensure the 2050 carbon reduction targets met [59]. In order to simulate the renewable-powered BESS model for future energy scenarios, the two degrees scenario for electricity generation by source and national demand were applied to the actual base year dataset. The electricity growth profiles in FES, with an assumption that they will follow the pattern in 2016, were applied to both renewable generation and electricity demand profiles to represent possible 2020 and 2035 energy scenarios.

The percentage increase of wind and solar, wind-solar mix and total gross demand of electricity from 2016 to 2020 and to 2035 in FES are shown in Table 1. Interestingly, there is no increase in demand prediction in 2020 from baseline 2016, though the overall and wind and solar generation are expected to increase. However, in 2035 the national demand will increase to 356 TWh from the baseline 328 TWh in 2016. The projections for 2020 were characterised by what the UK energy and emissions system would look like based on the implementation of

Table 1
Growth of wind and solar generation and demand forecasts in future energy scenarios [59].

	2016 (base year)		2020			2035		
	TWh	Wind-solar mix, %	TWh	Increase, %	Wind-solar mix, %	TWh	Increase, %	Wind-solar mix, %
Wind [a]	38.10	81.7%	62.67	64.48%	85.3%	143.73	277.2%	85.4%
Solar	8.53	18.3%	10.74	25.9%	14.7%	24.51	187.3%	14.6%
Total national demand (gross) [b]	328	–	328	0%	–	356	8.53%	–

[a] Total wind generation including offshore and onshore generators.
[b] Demand from generators (station demand), pumping demand (pumped hydro storage sites) and electricity storage (mostly batteries) are not included.

current and planned electricity sector policies with no further changes or additions. This was based on central predictions for fossil fuel prices, GDP and population growth. After 2020, the figures include assumptions that go beyond current government policy and can therefore only be used for illustrative purposes due to the inherent level of uncertainty.

2.4. Environmental impacts assessment

To assess the benefits of replacing CCGT variable generation by BESS, life cycle assessments (LCA) for both technologies were carried out. LCA is an environmental management tool that calculates the environmental impacts of a product or system over its entire life, from cradle to grave [60]. The LCA methodology in this study follows the approach laid out by ISO 14040 [61] and ISO 14044 [62]. SimaPro 8 [63] software package was used to model the LCA of CCGT and BESS. The LCA of BESS for grid level applications in Germany conducted by Immendoerfere et al. [35] was adapted for UK applications. The adaptation was made primarily in the use stage where authors in Ref. [35] assumed that the battery is charged with the electricity from German grid-mix while we consider the battery to be charged with electricity from UK wind-solar mix.

2.4.1. Goal and boundary definition

The goal of the LCA for this study is to calculate environmental and human health impacts due to electricity generation from CCGT and BESS for the UK grid. The functional unit of this study was set to 1 kWh of electricity generated from these technologies.

Environmental and health impacts caused by CCGT and BESS in their full life cycles must be considered in order to make informed decisions on technology investments. The system boundary of CCGT power plants and BESS for the LCA cover the “cradle to grave” approach as shown in Figs. 4 and 5. The CCGT life cycle stages comprises fuel provision, plant construction, operation and maintenance, and decommissioning activities. The life cycle stages for BESS consists of production of batteries, use and end-of-life activities. The use stage for BESS considered infrastructure development activities, operation and maintenance, life cycle impacts due to electricity generated from wind-solar mix to charge batteries, and efficiency losses. For both the CCGT and BESS cases, electricity transmission and distribution activities were excluded.

2.4.2. Data and assumptions for LCA study

The CCGT used for this study is located in the UK that has an installed capacity of 400 MW with a gas turbine capacity of 260 MW and steam turbine capacity of 140 MW, as can be found in Ecoinvent database [64]. The data for raw material (gas) extraction, processing and transport to the plant was obtained from ELCD (European reference Life Cycle Database) [65] and adapted for UK applications. The ELCD was established by the European Commission’s joint research centre and integrated in the SimaPro LCA software. The rest of the CCGT data, infrastructure, operation and maintenance, and decommissioning, for this study was obtained from Ecoinvent 3 database via SimaPro, which updated its database in 2016 [63]. The batteries considered in this research were a modular type lithium-manganese (Li-Mn2O4) that has a rating of 9.6GW/9.6 GWh (each module: 5MW/5 MWh) [35,49]. Battery data was obtained from two different sources: Ecoinvent [64] for raw material extraction, battery manufacturing, buildings construction for batteries, factory building services, UK wind-solar mix impacts data, decommissioning, disposal and recycling of batteries, and WEMAG store in Schwerin [54] for battery performance, energy data for maintenance, control and management systems [35].

The details of all other data and assumptions made in this research are given in Table 2. The efficiency of the CCGT plant in Ecoinvent is reported as 50–60%. For this study it was assumed to be 55%. An average lifetime for CCGT was assumed to be 25 years [66], whereas a lifespan of 20 years for BESS [34,35] was used for this study. The 20 years of lifespan is also covered under the warranty period provided by the manufacturer of WEMAG battery [54].

2.4.3. Impact category selection

The environmental impacts studied in this paper include (100 year time horizon) global warming potential (GWP), ozone depletion potential (ODP), terrestrial acidification potential (TAP), terrestrial ecotoxicity potential (TETP), freshwater eutrophication potential (FWEP), freshwater ecotoxicity potential (FWETP), marine eutrophication potential (MEP), photochemical oxidant creation potential (POCP), agricultural and urban land occupation potential (ALOP and ULOP), natural land transformation potential (NLTP) and metal depletion potential (MDP). These impacts were calculated using the ReCiPe [68] method. In addition, USEtox method was adopted for the calculation of human toxicity potential-cancer (HTP(c)) and human toxicity potential-non-cancer (HTP(nc)).

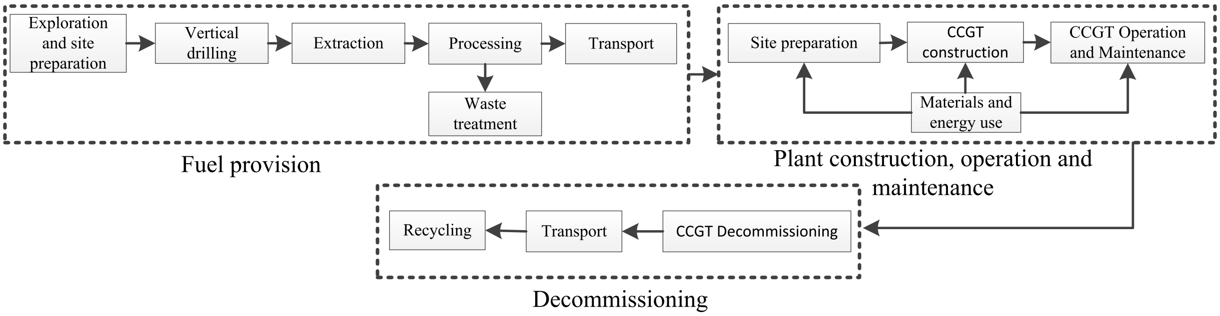

Fig. 4. LCA boundaries of CCGT .

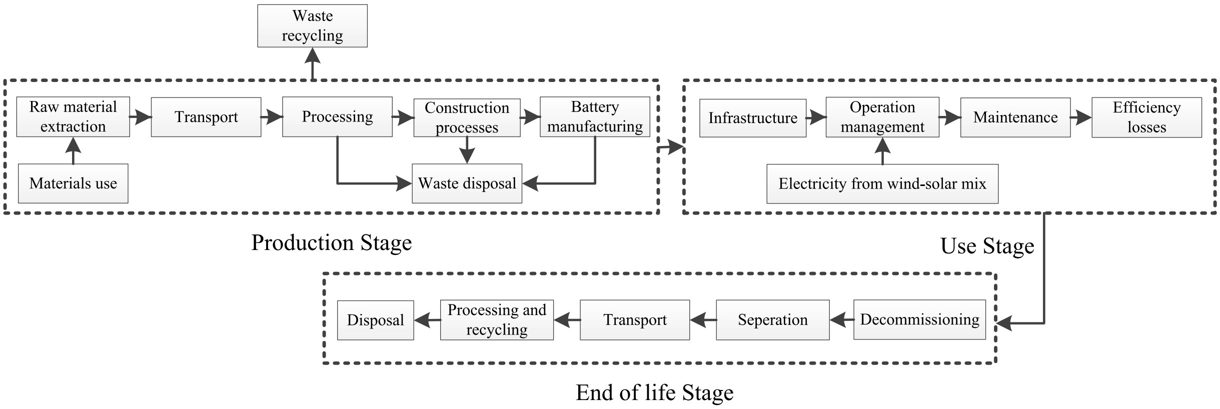

Fig. 5. LCA boundaries of BESS.

Table 2
Data and assumptions of CCGT power plant and BESS considered in LCA analysis.

Properties	CCGT	Source	BESS	Source
Plant rating	400 MW (260 MW gas+ 140 MW steam)	[64]	9.6GW/9.6 GWh (Each module: 5MW/5 MWh, cell type: Lithium-manganese-oxide, cell no.: 25600, cell manufacturer: Samsung SDI [49])	[35]
Efficiency	55% (thermal)	[66]	72.5% (round-trip)	[35]
Lifetime	25 years	[64]	20 years (max. best practice)	[34]
Performance deterioration	N/A		20% in 20 years	[35]
Annual operation hours/cycles	7200 h	[64]	194 cycles	[35]
Electricity generated per year	1287 GWh/year[a]	[64]	1855 GWh/year	[35]
Raw materials extraction, processing and transport	Data from ELCD based on total gas used in the power plant	[65]	Ecoinvent data for Li-Mn2O4 battery. 1 kg battery pack production needs: Single cell: 0.799 kg (per kg single cell-Cathode: 0.327 kg, Anode: 0.401 kg, Separator: 0.0537 kg) Steel box material: 0.145 kg Battery management system, mounting: 0.00338 kg Other inputs data from the reference	[67]
Infrastructure and decommissioning	Ecoinvent data for infrastructure that includes plant construction, decommissioning and waste treatment	[63]	Ecoinvent data for factory building constructions, services, storage infrastructures, decommissioning, disposal and recycling of batteries	[63]
Plant operation and maintenance	Ecoinvent data for all operation and maintenance activities and materials of the power plant	[63]	Self-consumption: 0.379 MWh/MWh$_{generated}$ (Electricity uses for operation, control and management systems including losses from WEMAG store) Wind-solar mix in the UK was used to charge the BESS[b] Ecoinvent data for LCI of wind and solar in the UK. Wind plant size: >3 MW, onshore Solar PV size: 3kWp, installed on a household's roof-space	[35] [63]
Other data	Gas composition: Methane: 96.5% Ethane: 1.8% Propen:0.45% Others: 1.25% Calorific value: 49.18 MJ/kg Average gas use: 0.14 kg/kWh	[63]	Battery energy density: 114 Wh/kg	[35]

[a] It was assumed that a linear scaling of CCGT to generate 1855 GWh/year would be required so that BESS and CCGT supplies the same amount of electricity in a year.

[b] WEMAG batteries in Ref. [35] were used to charge by the electricity from German grid-mix. In our paper, the batteries were charged with the electricity from UK wind-solar mix. Hence, LCI data for UK wind-solar mix was obtained from Simapro via Ecoinvent database.

3. Results and discussions

The storage model described in Section 2 was applied to the base year, 2016, and future energy scenarios, 2020 and 2035, to determine the size of storage and the amount of variable peak demand that can be supplied with BESS instead of CCGT. Results from the simulation and LCA of BESS and CCGT are presented in following sections.

3.1. *Partial offsetting of CCGT generation*

Partial offsetting of CCGT means BESS only able to supply a fraction of total variable demand while the rest of the demand has to be supplied by CCGT. This can happen when a grid does not have adequate RES generation capacity and at the same time there is a lack of sufficient excess energy from wind and solar to be stored in batteries. Even though in some times of the day, there might be significant amount of excess energy and BESS alone might supply the peak demand. The same is true for the opposite where CCGT might supply all excess demand. Depending on excess generation, excess demand and power mismatch, partial load offsetting in different forms can be achieved.

3.1.1. *Base year analysis*

The electricity demand and supply profile retrieved from the UK National Grid for 2016 was modified according to the research

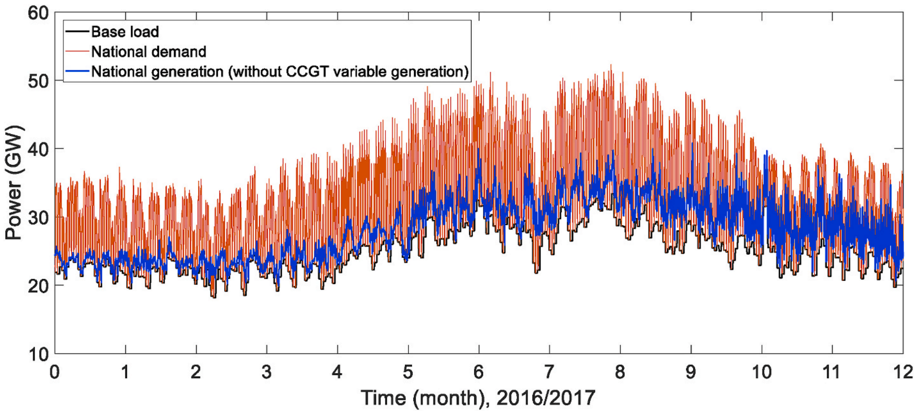

Fig. 6. Electricity demand and supply profile without CCGT variable generation in 2016.

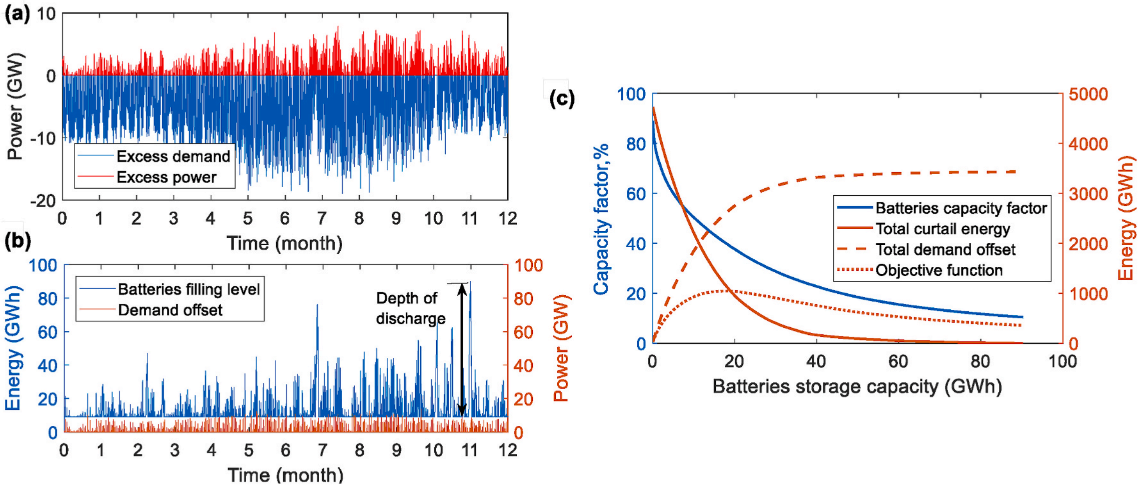

Fig. 7. Base year 2016 (a) power mismatch, (b) instantaneous filling level of batteries with infinite size and demand offset, (c) batteries capacity factor, total curtail energy, total demand offset and objective function.

methodology presented in Fig. 2 and shown in Fig. 6. The baseload demand in the profile is the minimum load of a day which is supplied by major baseload plants, while the variable peak load is to be supplied from non-programmable RES such as wind and solar and programmable RES such as pumped hydro and BESS, and CCGT variable generators. Fig. 6 also shows the national electricity generation without the CCGT portion for the base year. Practically, most of the excess demand is met by CCGT peak power plants. Nonetheless, in this research we used BESS to supply some of these excess demands which would otherwise come from CCGT.

The power mismatch between supply and demand in the base year is shown in Fig. 7(a). The positive mismatch is the excess power available at the grid and the negative is the excess demand. It can be seen from this figure that the average excess power to charge the batteries is less than the average excess demand over a one year period. The charge and discharge of BESS model follows Eq. (3) with infinitely large capacity for

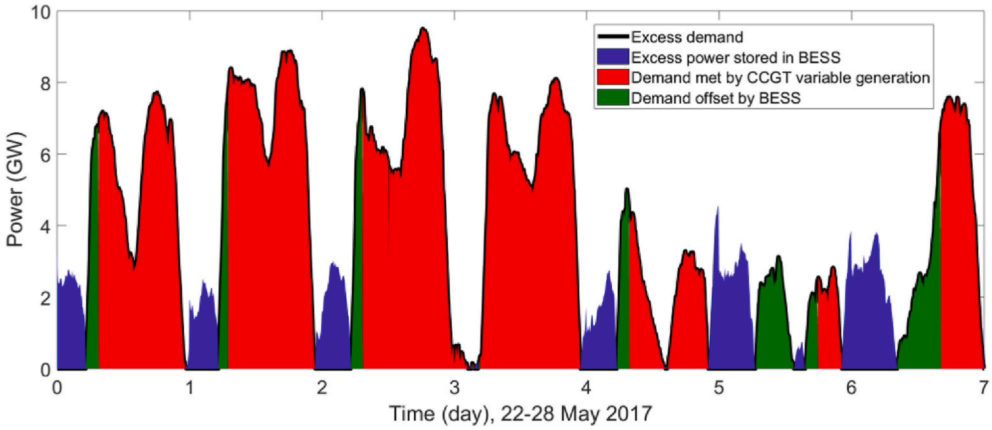

Fig. 8. Supply and demand balancing with batteries and CCGT in a representative week (22–28 May) in 2017.

entire period as shown in Fig. 7(b). The depth of discharge of the storage considered in this model was restricted to 90% of full capacity. As can be seen from the figure, the BESS was initially charged from zero and then limited to DOD for entire year. Based on the excess power and excess demand in Fig. 7(a), the filling level of the infinitely large storage is increased or decreased accordingly, and hence fulfilling some or all variable demands. Fig. 8 shows the outputs of the BESS model and the supply and demand management of variable load for a representative week in 2017. It can be seen from this figure that when the demand is low (usually from midnight to the morning, around 6 a.m.) and there is excess energy, the battery stores energy and it starts to discharge once the demand is above baseload and fulfilled some excess demand while the rest of the demand was still fulfilled by the CCGT generators. Based on the filling levels, the estimated maximum size of the BESS calculated in Eq. (7) and shown in Fig. 7(b) is found to be$BS_{\max,\inf} = 89.83$ GWhfor 2016. This size is orders of magnitudes higher than the total installed capacity of electrical storage (15.3 GWh, excluding pumped hydro) in the world in 2017 [69]. Since the objective of the infinitely large storage model was to capture all excess energy from solar and wind, the curtailed energy is zero, as shown in Table 3. The maximum size$BS_{\max,\inf}$can offset a theoretically highest amount of CCGT variable generation, which is 3431 GWh (8% of CCGT) in 2016. A capacity factor for the maximum infinite storage in 2016 was found to be 10.46% only, which was due to a low annual demand offset (3431 GWh) compared to the maximum annual capacity of the battery (89.83 GW × 365 day), based on a single charge/discharge cycle per day. Even though the storage was allowed to charge and discharge daily, due to availability of excess energy from wind and solar and an excess demand at the grid, the BESS may not be charged and discharged every day. This limitation gives a low capacity factor of BESS, as it was the case here. That means, only around 11% of the storage capacity was used for storing and delivering energy over the investigated time and the rest of the capacity was not serving the purpose. Also, the estimated BESS capacity factor is much lower than the current capacity factor of CCGT (31.7%), or wind (33.7%) plants in the UK [70]. Therefore, an optimisation of the size of batteries considering the capacity factor and delivered output was carried out and the results of the simulation are shown in Fig. 7(c) and Table 3. Fig. 7(c) represents the outputs of the simulation such as batteries capacity factor, total curtailed energy, total demand offset and the objective function for batteries with a size starting from $BS = 1$ to$BS_{\max}$. As the size of batteries increases the variable demand offset increases exponentially, whilst at the same time the capacity factor and curtailed energy decrease exponentially. The objective function which is the multiplication of these two opposite variables is shown in Fig. 7(c). The maximum of the objective function is the optimal size of batteries which is a compromise choice ensuring both the capacity factor and the demand offset are in a mutually highest point. The optimal size of batteries for 2016, 17.58 GWh (which is less than the size of$BS_{\max,\inf}$), is capable of delivering 2588 GWh (6.04%) of variable demand at a capacity factor of 40.32%. The capacity factor for the optimal storage size has increased significantly due to significant reduction of storage size (from 89.83 GWh of maximum infinite size to 17.58 GWh of optimal size). This indicates that the batteries were charging and discharging more frequently in an optimal case than that of a non-optimal case. However, this optimal size could not store all excess energy from wind and solar due to size limitation and thus 1178 GWh of excess energy had to be curtailed in the base year.

3.1.2. *Future scenario analysis*

Results for the selected future scenarios, 2020 and 2035, are given in Table 3 and shown in Figs. 9 and 10, respectively. Despite wind and solar generation being expected to increase to 64.48% and 25.9% in 2020 from the baseline 2016 (Table 1) the average excess generation is still lower than the average excess demand shown in Fig. 9(a). As a result, a maximum size of infinitely large battery, 442.58 GWh, calculated from Fig. 9(b) with Eq. (7) was unable to supply all variable peak demand as can be seen in Table 3. Even though this size is much higher than the size calculated for 2016, CCGT supply was still needed due to the lack of sufficient excess electricity to store which could meet all the variable demand. However, the maximum size of batteries was used only once a year as can be seen in Fig. 9(b), and hence the capacity factor of batteries at this size was found to be very low, 4.70% in this case. An optimal size of batteries for 2020 scenario was evaluated taking the maximum of the objective function shown in Fig. 9(c), which was found to be 29.25 GWh. At this size the batteries were able to offset 4511 GWh (13.5% of variable demand) of electricity during peak times, while the CCGT had to supply around 28807 GWh. The optimal size has therefore a better capacity factor, 42.25%, on one hand and cause the grid to curtail around 4332 GWh excess generation from wind and solar plants on the other hand.

Fig. 10 shows the BESS model and the scenario outcomes for 2035. Unlike 2016 and 2020, the future scenario 2035 has so much wind and solar generation that the average excess power surpasses the average excess demand (Fig. 10(a)). In such conditions, the model with infinitely large size causes a drift in the instantaneous filling level of the batteries which can be seen in Fig. 10(b). That means, over a period the battery was storing more energy than what was required at the grid (see Fig. 10 (b) and (c)), which does not make sense from a supply and demand management point of view. In order to take care of the drift, a maximum size of batteries restricted by Eq. (6) was applied in all similar cases presented in the paper. Instead of maximum infinite size, the model had estimated a maximum finite size of 1603.40 GWh that could deliver around 15708 GWh (82.3%) of variable demand in 2035 at a capacity factor of 2.70% (see Table 3 and Fig. 10 (d)). Since the size of batteries was restricted the curtailed energy was not of a technical concern and therefore is not presented in Fig. 10 (d). Under this circumstance, the CCGT still had to supply 3374 GWh electricity in 2035, which is much lower than what we obtained for 2016 and 2020. However, because of the low capacity factor, techno-economic benefits of the maximum size of BESS is expected to be low. Thus, an optimal size of 45.9 GWh and its corresponding capacity factor of 33.13% were estimated that could supply 5553 GWh (29.1%) of energy at peak times.

3.2. *Full offsetting of CCGT generation*

One objective of this paper was to investigate the amount of renewable generation and storage needed to phase out CCGT variable generation completely from the UK grid. In order to achieve it, the

Table 3
Results for partial offsetting of CCGT variable generation in base year and future scenarios.

Sizing criteria	Year	Battery capacity,	Variable peak demand offset,		Curtailed electricity,	CCGT supply,	Capacity factor,
		GWh	GWh	%	GWh	GWh	%
Maximum infinite storage	2016	89.83	3431	8%	0	39448	10.46%
Optimal storage		17.58	2588	6.04%	1178	40292	40.32%
Maximum infinite storage	2020	442.58	7603	22.8%	0	25716	4.70%
Optimal storage		29.25	4511	13.5%	4332	28807	42.25%
Maximum finite storage	2035	1603.40	15708	82.3%	17783	3374	2.70%
Optimal storage		45.9	5553	29.1%	33587	13529	33.13%

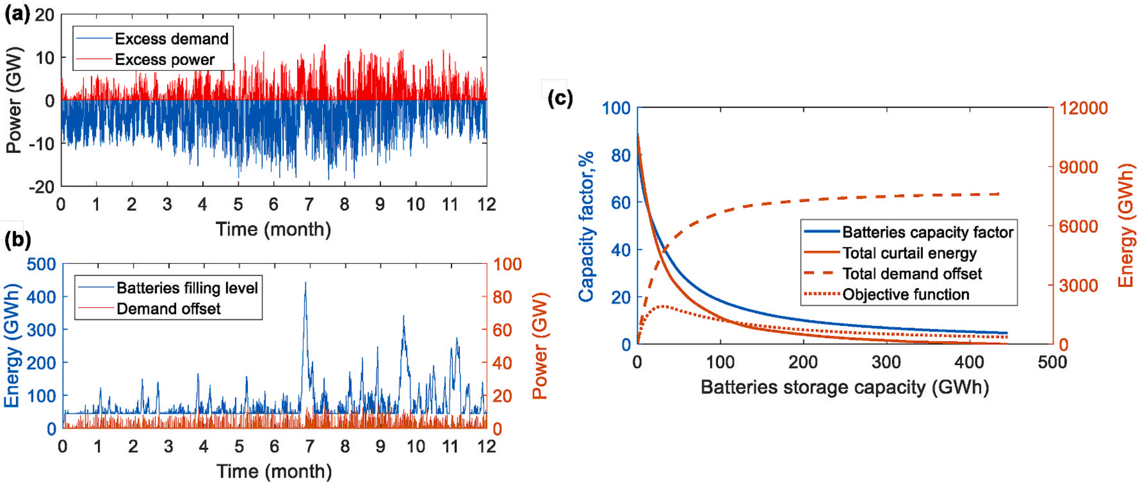

Fig. 9. Future scenario 2020 (a) power mismatch, (b) instantaneous filling level of batteries with infinite size and demand offset, (c) batteries capacity factor, total curtail energy, total demand offset and objective function.

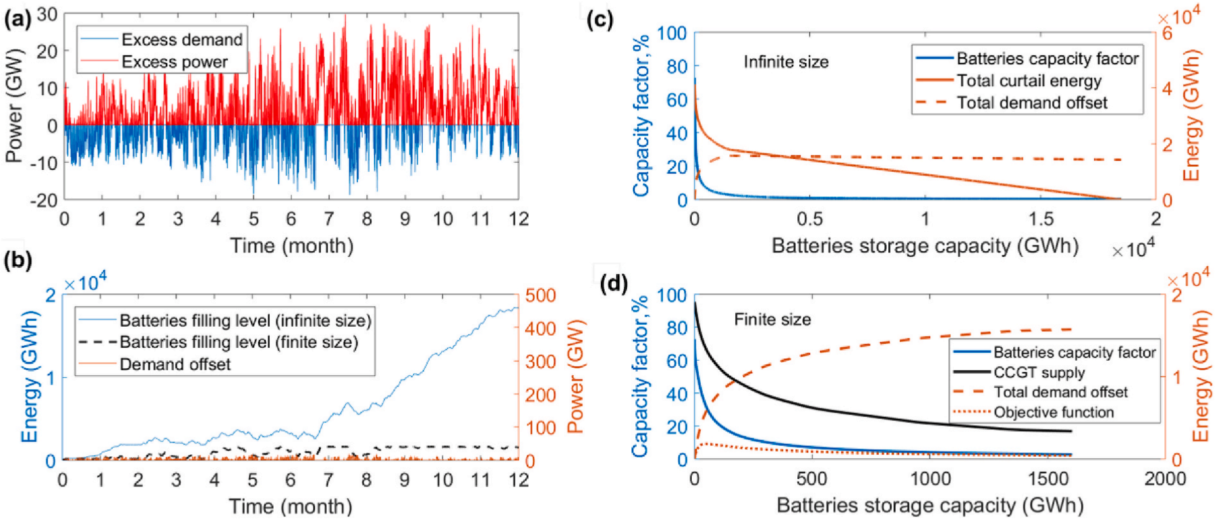

Fig. 10. Future scenario 2035 (a) power mismatch, (b) instantaneous filling level of batteries with infinite and finite size and demand offset, (c) batteries capacity factor, total curtailed energy and total demand offset with infinite batteries size, (d) batteries capacity factor, CCGT supply, total demand offset and objective function with finite size.

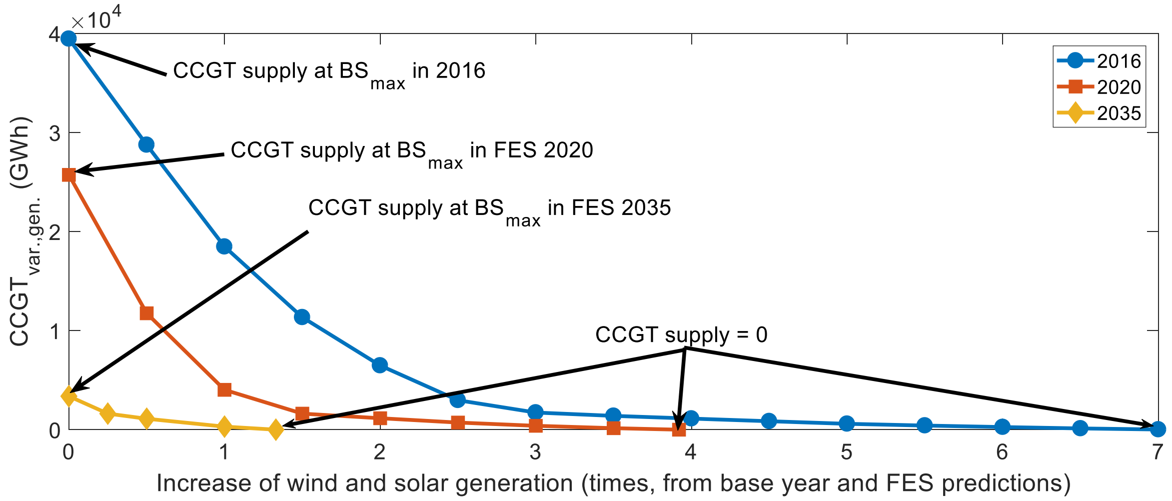

Fig. 11. Increase of wind and solar generation needed to fully offset CCGT variable generation in base year and future scenarios.

amount of RES generation, wind and solar, was increased while the supply from other generators and national demand in 2016, 2020 and 2035 were kept constant until the CCGT's contribution became zero (see Fig. 11). This excess generation requirement implies that additional generation capacities would need to be installed. Additionally, due to the non-programmable nature and uncertainty of wind and solar sources to generate the required amount of power at the right time, the UK grid must have a safety margin of its RES installation capacities. However, the current study focuses only on the generation requirement and not the installation capacities of RES. Furthermore, it was assumed that the shares of wind and solar in the wind-solar mix in additional generations are same as they were in base year and FES (see Table 1). Results show that, in base year 2016, 7 times more wind and solar would be needed to offset the CCGT variable generation completely. However, due to higher generation capacities of wind and solar in FES predictions, additional generation requirements had reduced to 3.90 and 1.33 times of the predicted capacities in 2020 and 2035, respectively (see Fig. 11).

The model with increased wind and solar generation was simulated for base year and future scenarios and the outputs are shown in Table 4. The maximum finite size of batteries for 2016 and 2020 were estimated at 868.50 GWh and for 2035 at 948.25 GWh, and the corresponding results are shown in Table 4. It can be seen from Table 4 that the storage size for both 2016 and 2020 is the same. The reason is that the national demand prediction in 2020 is the same as in 2016, and thus needs the equal amount of wind and solar generation to offset CCGT completely. Although, the CGGT supply became zero with the increased amount of RES generations (see Fig. 11) and maximum finite size battery, the capacity factors of BESS, however, for all the scenario years were found to be very low, 1.84% for 2016 and 2020 and 1.85% for 2035. This is primarily due to a low and intermittent excess demand (or hence the demand offset) across the year. Therefore, to fully offset CCGT generation, BESS only is not a viable option. Although, we did not use the influence of interconnectors in managing supply and demand in this paper, the role of interconnectors to offset CCGT fully seems an interesting option. Therefore, we investigated, briefly, a combined role of BESS and interconnectors to phase out CCGT for supplying variable peak demand.

To find an optimal mix of BESS and interconnectors, we optimised the battery size and estimated the required amount of interconnectors supply (see Table 4). An optimal size of 56.75 GWh battery calculated for 2016 and 2020 could supply 55.80% of variable peak demand (3265 GWh), while rest of the demand (2589 GWh) was estimated to have supplied from interconnectors. To ensure a zero CCGT supply in 2035, an optimal battery size of 62 GWh would be required. The battery at this size could supply 3573 GWh (55.85% of total peak) of peak variable demand at a capacity factor of 15.80%. Interconnectors in the optimal mix hence would have to supply 44.15% (2825 GWh) of peak electricity to the UK grid. The estimated interconnectors supply is much lower than the predicted supply in National Grid FES. For example, in 2016, the net import was estimated at 14.97 TWh and in 2020, it was 37.83 TWh [59]. Even though in 2035, the UK will become a net exporter via interconnectors, as mentioned before, still there will be some imports to the UK grid that may supply the required peak demand that was estimated in this research. However, a further comprehensive study will require to understand the roles of interconnectors in peak demand management and the synergies among BESS, renewable generation, baseload plants, and interconnectors supply.

3.3. *Life cycle impacts analysis*

3.3.1. *Life cycle impact comparison*

Table 5 shows the environmental and human health impacts of CCGT and BESS from the simplified LCA analysis for 2016, 2020 and 2035. Based on these results, one can notice that there are some impact categories of BESS which are less harmful to the environment than the CCGT. This is the case for global warming potential (GWP) and ozone layer depletion potential (ODP) which are responsible for global warming and climate change. The electricity from CCGT was estimated to emit 0.41 kg CO_2 eq./kWh compared to 0.0584 kg CO_2 eq./kWh for the battery technology used in this paper. This implies the GWP of BESS is 86% lower than for CCGT in 2016. Most of the GWP for both technologies are from their operation stages due to direct combustion of gas in CCGT and the charging of battery units with electricity that accounts for the life cycle emissions of upstream processes in wind and solar plants. Likewise, BESS has at least 52% lesser impact than the CCGT in terms of ODP, which was estimated at 0.00806 mg CFC-11 eq./kWh for BESS in comparison to 0.017 mg CFC-11 eq./kWh for CCGT. Apart from these two key factors, terrestrial acidification potential (TAP), photochemical oxidant formation potential (POCP) and natural land transformation potential (NLTP) impacts for BESS are also lower than CCGT. In particular, since battery technology has the advantage of modularity properties to place on land without significant land transformations, the NLTP for BESS is much lower (93%) than for CCGT (see Table 5). Furthermore, POCP of BESS emits 0.24 g NMVOC/kWh, which is 42% lower than for CCGT (0.41 g NMVOC/kWh). The majority of the POCP is due to emissions of SO_2, NO_x and CO from the combustion process in CCGT. The TAP for BESS was estimated at 0.283 g SO_2 eq./kWh, which is 23% lower than for CCGT (0.367 g SO_2 eq./kWh). Although BESS is more environment friendly in terms of GWP, ODP and others, it has more negative consequences in terms of eutrophication potentials (FWEP and MEP) and human toxicity and occupies much more land (agricultural and urban) than CCGT. These impacts categories are more harmful (in the range of 244%–1218%) with BESS than CCGT as can be seen in Table 5 for base year analysis. The single biggest negative impact of BESS, metal depletion potential (MDP), is 1218% more (43.5 g Fe eq./kWh) than CCGT (3.3 g Fe eq/kWh). This is as expected due to extensive use of metals for the manufacturing of batteries [71], and the metal use for wind and solar plants that used to charge BESS in this study. The rest of the negative impact categories have lower consequences to either the environment or to human health as they are in an order of micro units as shown in Table 5. More specifically, the human health toxicity potential with BESS has 0.0129 μCTUh/kWh for HTP (cancer) and 0.1193 μCTUh/kWh for HTP (non-cancer), which are an order of magnitude higher than the CCGT due to human exposures to toxic materials during mining, processing and production of batteries.

To estimate the life cycle impacts of BESS in future scenarios 2020

Table 4
Results for full offsetting of CCGT generation in base year and future scenarios.

Sizing criteria	Year	Battery capacity, GWh	Variable peak demand offset, GWh	Variable peak demand offset, %	CCGT supply/Interconnectors[b] GWh	CCGT supply/Interconnectors[b] %	Capacity factor, %
Maximum finite storage	2016/2020	868.50	5854	100%	0	0	1.84%
Optimal mix[a]		56.75	3265	55.80%	2589	44.20%	15.76%
Maximum finite storage	2035	948.25	6398	100%	0	0	1.85%
Optimal mix		62	3573	55.85%	2825	44.15%	15.80%

[a] Optimal mix consist of electricity supply from batteries with optimal size and interconnectors.

[b] Instead of employing large batteries without interconnectors, an optimal mix of batteries (optimal size) and interconnectors can be used to fully offset CCGT variable generation from the UK grid.

Table 5
Life cycle environmental and health impacts of CCGT and BESS per kWh of electricity output for 2016, 2020 and 2035.

Impact category	Life cycle impacts						
	CCGT[a]	BESS[b]			% change from CCGT to BESS		
	2016/2020/2035	2016	2020	2035	2016	2020	2035
GWP, kg CO_2 eq/kWh	0.41	0.058	0.054	0.053	−85.85	−86.83	−87.07
ODP, mg CFC-11 eq./kWh	0.017	0.00806	0.00752	0.00751	−52.59	−55.76	−55.82
TAP, g SO_2 eq./kWh	0.367	0.283	0.294	0.295	−22.89	−19.89	−19.62
FWEP, mg P eq./kWh	6.57	80.8	77.18	77	+1129.83	+1074.73	+1071.99
MEP, mg N eq./kWh	13.4	46.13	44.17	44	+244.25	+229.63	+228.36
POCP, g NMVOC/kWh	0.415	0.24	0.225	0.224	−42.17	−45.78	−46.02
ALOP, m^2a/kWh	0.00069	0.00357	0.00325	0.00324	+417.39	+371.01	+369.57
ULOP, m^2a/kWh	0.000218	0.00124	0.00121	0.00120	+468.81	+455.05	+450.46
NLTP, m^2/kWh	0.000176	1.14×10^{-05}	1.09×10^{-05}	1.09×10^{-05}	−93.52	−93.81	−93.81
MDP, g Fe eq./kWh	3.3	43.5	42.65	42.63	+1218.18	+1192.42	+1191.82
USEtox - HTP(c), μCTUh/kWh	0.00186	0.0129	0.0127	0.0127	+593.55	+582.80	+582.80
USEtox - HTP(nc), μCTUh/kWh	0.00931	0.1193	0.1169	0.1168	+1181.42	+1155.64	+1154.56

[a] CCGT impacts are assumed to be constant for different scenario years.
[b] BESS impacts are changed according to wind-solar mix of the UK grid as predicted by the National Grid's future energy scenario (see Table 1).

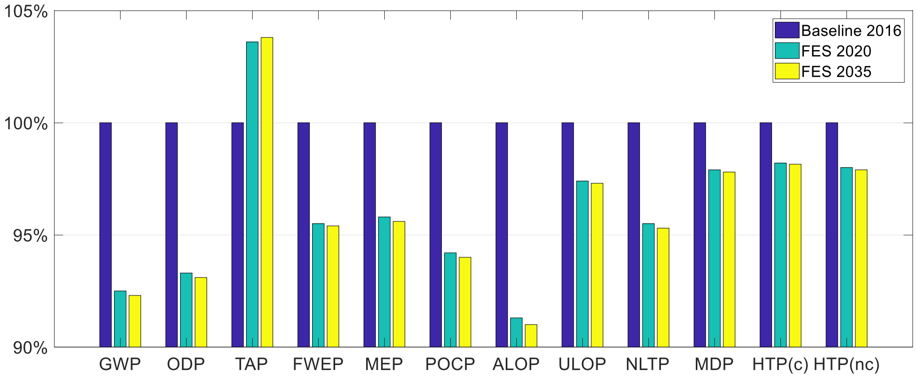

Fig. 12. Environmental and health impacts per kWh of electricity output from BESS for future energy scenarios 2020 and 2035 from baseline 2016 (baseline = 100%).

and 2035, the operation stage impacts due to charging of batteries were calculated according to the wind-solar mix at the time as shown in Table 1. All other impacts such as production and disposal for BESS and all impact of CCGT per kWh were assumed constant. The results of environmental and human health impacts in 2020 and 2035 shown in Table 5 are compared with the baseline 2016 and shown in Fig. 12. As can be seen from the figure, all impacts per kWh of electricity estimated in this research for 2020 and 2035 are lower than 2016, except TAP. This reduction is primarily due to reduction of solar contribution in wind-solar mix in the UK grid (see Table 1). For instance, the GWP of the solar plant was estimated at 0.142 kg CO_2 eq./kWh compared to 0.02 CO_2 eq./kWh for the wind farm from Ecoinvent. Thus, a decrease of the solar contribution in the wind-solar mix always causes a decline in the impact of GWP of the mix. Similarly, more contribution from wind to charge the BESS means the less impact we may have from battery operations. Most of the reduced impacts in 2020 and 2035 are within the range of 90–98% as shown in Fig. 12. However, there is only one impact category, TAP, which exceeded the baseline impact-100%, as can be seen in Fig. 12. The reason is that the solar PV (see Table 2) used in this research was installed on a household's roof space, thus fulfilling some of its demand and exporting most of the electricity to the grid. Hence, TAP for solar was found to be negative due to gross export of electricity

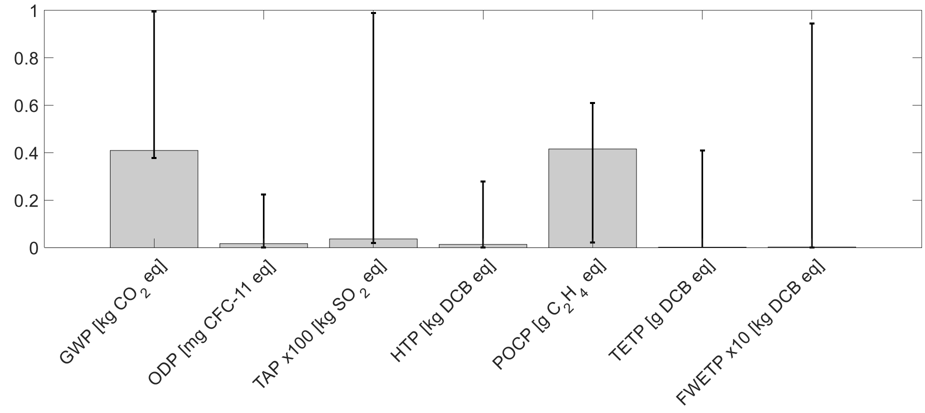

Fig. 13. Validation of CCGT's environmental impacts per kWh of electricity with results from literatures [5,66,73,74].

to the grid [72]. As the solar contribution to charge BESS is reduced in 2020 and 2035 from 2016, TAP has increased and exceeded the baseline level.

Compared to CCGT, the environmental and human health impacts of BESS in 2020 and 2035 follow the same way as for the 2016- some are positive and some are negative. However, the focus of the environmental benefits of grid-scale batteries to offset some of CCGT variable generation lies on the GWP savings. Results from Table 5 show that BESS in place of CCGT can save up to 86% and 87% of CO_2 eq. (/kWh-basis) in 2016, and 2020 and 2035, respectively. If this BESS is linearly scaled up and deployed to supply the optimal amount of variable peak demand that was calculated in Section 3.1, it can save an estimated GWP of 0.91, 1.61 and 1.98 $MtCO_2$ eq. in 2016, 2020 and 2035, respectively.

3.3.2. Validation of LCA for CCGT

The LCA studies of CCGT were compared with the results available in the literature [5,66,73,74] and are shown in Fig. 13. Key impacts such as GWP, ODP, TAP, HTP, POCP, TETP, FWETP are all within the range of values presented in the literature. It is worth noting that the minimum and maximum values of each impact found in the literature vary a lot depending on the LCA methodologies, background datasets, sources of fuel use, technology types, efficiency and location of CCGT plants used for their calculations. Nonetheless, all impacts presented in the literature are in per kWh which is also a functional unit in this LCA analysis. The GWP for this study were estimated at 0.41 kg CO_2 eq./kWh which is within the limit found in the literature (0.379–0.996 kg CO_2 eq./kWh). The ODP for CCGT has a range in between 1.34×10^{-6} and 0.224 mg CFC-11 eq./kWh compared to 0.017 mg CFC-11 eq./kWh in this research. All other values of the impacts were compared and can be seen in Fig. 13.

3.3.3. Validation of LCA for BESS

To validate the LCA of BESS in this study, we looked at the literature that considered an LCA of stationary BESS for grid applications. Although there are some studies that conducted an LCA for stationary BESS [34,35,75–77], most of them are limited to certain phases of life such as production and end-of-life [75], use phase [76], and production and use phase [34,77]. As we mentioned before, a complete life cycle studies including production, use and end-of-life of a stationary BESS can only be found in Ref. [35]. However the limitation of that study is that the use phase of LCA, the most responsible contributor to GHG emission as reported in Ref. [34,77], was conducted based on a BESS that was charged with the electricity from a grid mix, as was the case for the other study in Ref. [77]. Whereas, in our study, all the three phases of a life cycle and charging the BESS with wind-solar mix were considered. In order to validate our work, we selected the study of Mitavachan et al. [34] that considered a stationary BESS which was charged both with the electricity from renewable sources (solar/wind-solar mix) and with grid mix. Since the LCA of this study considered a life cycle with production and use phase but without the end-of-life stage of batteries, therefore, the current results of GWP without the end-of-life stage for the BESS at different electricity sources and grid mix intensity were compared to the reference values and are shown in Fig. 14. As can be seen from the Fig. 14(a), the GWP for the current study is 0.153 kg CO_2 eq./kWh compared to the reference value of 0.125 kg CO2 eq./kWh, if the battery is charged with the electricity from solar only. However, if the electricity source is changed to 50-50 wind-solar mix, the GWP is also changed to 0.092 kg CO_2 eq./kWh compared to the reference value of 0.072 kg CO_2 eq./kWh. Fig. 14(b) compares the GWP for the current study and the reference study in regards to grid mix carbon intensity. It can be seen from this figure that the GWP of batteries is increased with the increase of grid mix intensity and the results indicate the maximum discrepancy between the current and reference study is about 9%. The discrepancies between the studies are inevitable because of the LCA of wind and solar that have different impact values depending on location, methodological difference, and size of each studied technology [78]. In particular, due to location variations the life cycle impacts of wind and solar for the UK have different values than those studied in Germany in the reference paper.

4. Conclusions

This study investigated the potential of grid-scale battery (Li-ion) for offsetting CCGT variable peak electricity demand and its life cycle environmental and health impacts in the UK. Excess generation from wind and solar can be stored in batteries during times of low demand and discharged to the grid during times of high demand. Based on this method, an algorithm was developed to calculate and optimise the size of batteries needed to offset the variable peak demand which otherwise would come from CCGT. This model was applied to a recent year, 2016–2017, with electricity supply and demand data obtained from the National Grid, UK. The model was then applied to future energy scenarios 2020 and 2035 to investigate the potential where a number of variables such as wind and solar generation, national demand and generation have changed. The results indicate that partial load offsetting of CCGT variable generation is possible in each scenario analysis. For example, the optimised supply from batteries during peak times in 2016, 2020 and 2035 can be up to 2588 GWh, 4511 GWh and 5553 GWh, respectively. It is worth noting that these demand offset were obtained with the data available from the National Grid that has some inaccuracy due to lack of information on solar and unmetered wind generation, as discussed in section 2.3. Therefore, the results presented in this paper could be changed slightly for actual data on the UK electricity supply and demand. Nonetheless, phasing out of variable CCGT generation

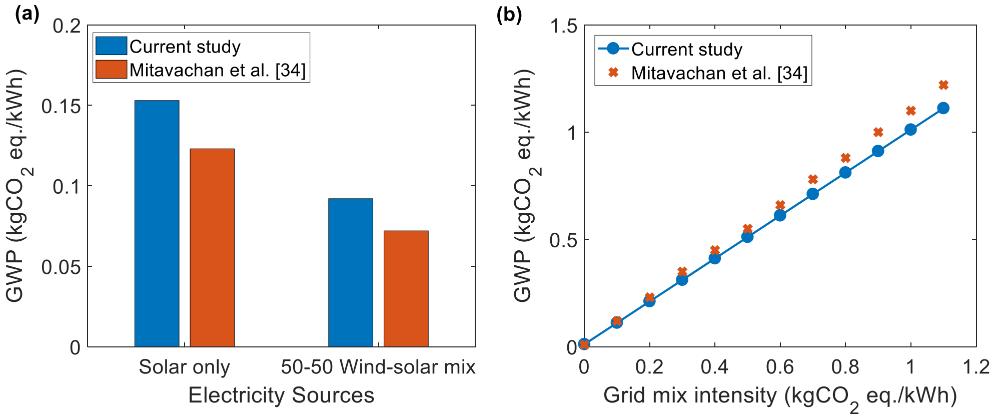

Fig. 14. Validation of BESS GWP impacts, (a) batteries charge with different electricity sources, (b) batteries charge with electricity from UK grid at different carbon intensity.

from the UK grid requires significant increase of wind and solar generation capacities (up to 3.90 times in 2020 and 1.33 times in 2035, from their baseline values in FES) and battery size. Because of the inherent variable nature of wind and solar generation and uncertain demand, full offsetting of CCGT variable generation with BESS only seems to be unrealistic as the capacity factor of batteries becomes very low (up to 1.85%). However, an optimised BESS and interconnectors may pave the way for phasing out of CCGT variable generation. To confirm this initial finding, a further comprehensive study is needed, which will be a task for future research.

Likewise the technical analysis, the LCA of the battery was also conducted for the year 2016, 2020 and 2035. The results of LCA for the battery were compared with that of the CCGT for per kWh electricity output. The results suggest that the battery has much lower environmental impacts in GWP, ODP, TAP and NLTP than the CCGT studied in this paper. For example the GWP of battery was estimated at 0.058 kg CO_2 eq./kWh in 2016, which is 86% lower than the value for CCGT (0.41 kg CO_2 eq./kWh). Therefore the potential savings of GWP with the studied battery, if scaled up to deliver the variable peak demand mentioned earlier, can be up to 0.91, 1.61 and 1.98 $MtCO_2$ eq. in 2016, 2020 and 2035, respectively. However, these saving is to be realised in a detailed techno-economic analysis in future.

This research simplified the life cycle environmental impact analysis in some ways including an assumption of 194 full cycles/year of battery in its 20 years lifetime. However, batteries are not likely to be fully discharged/charged because the available excess energy or excess demand and the limitation of depth of discharge, which was assumed 90% to ensure safety and battery lifespan. Therefore, the results presented in this paper may change significantly if the depth of discharge, number of full cycle/year and the lifetime of batteries are changed. Furthermore, the LCA for future scenarios is also simplified by assuming the production and end-of-life stage of batteries to remain stable for the next 20 years. Moreover, improvements in energy efficiency and battery energy density over a 20-year period are not accounted in this research. Hence, further work should consider these factors which to be explored in future. Our findings present how energy storage systems can play significant roles in decarbonising electricity grids which is essential for mitigating climate change. Further expected developments in the efficiency of storage technologies will probably improve these benefits.

Credit author statement

J.I. Chowdhury: Technical and LCA modelling, analysis, leading the manuscript writing, N. Balta-Ozkan: Conceptual development, reviewing and supervision, P. Goglio: Conceptual development, LCA software and data support, Y. Hu: Reviewing and editing, L. Varga: Reviewing, editing and supervision, and L. McCabe: Writing and reviewing.

Declaration of competing interest

The authors declare that there is no conflict of interest in this work.

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