Achieving both Economic and Environmental Objectives for a Solar Farm with Co-located Battery

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***Abstract*— Energy storage must play a part in a future world powered by intermittent low-carbon sources such as wind and solar power. It is often taken for granted that grid-scale battery storage is too expensive unless offering multiple ancillary services to the electrical grid, rather than just absorbing and later exporting renewable energy that would otherwise be curtailed. This belief is confirmed and quantified in this work, by simulating a solar PV farm with generation capacity exceeding its grid export limit, using battery storage to avoid some curtailment. The required carbon price for the system to break even financially, when optimizing for lifetime CO_2 emission savings, is well above even the World Bank's recommendation to avoid catastrophic climate change. This indicates the need for dramatic reduction in the cost of energy storage, and for revenue streams in addition to simply the sale of otherwise-curtailed energy.**

Keywords- solar PV; battery; curtailment avoidance; CO_2 emissions; techno-economic analysis

I. Introduction

To combat the threats posed to productivity, infrastructure and public health by climate change and air pollution, many countries around the world are developing plans to de-carbonize their economies [1], [2], [3].

It is widely accepted that energy storage must play some role in balancing the intermittent supply from wind and solar photovoltaic generation [4]. When it comes to the financial viability of energy storage systems, numerous techno-economic analyses have shown its value when used with renewable power in microgrid systems [5], [6]. When a community or base station is very remote, the cost of diesel deliveries for generators or maintaining a long connection to the main electrical grid is high, and the option of renewable energy with storage becomes comparatively favorable [7]. But given that the global population is rapidly urbanizing, and demanding more reliable access to energy, microgrids cannot be relied upon to remain an attractive value proposition [8].

While home batteries such as the Tesla Powerwall offer savings to a homeowner by allowing them to store and use more electrical energy from a rooftop PV array [9], [10] (reducing grid import/export caused by mismatch in instantaneous demand and generation), they do not reduce a country's overall carbon emissions: 1 kWh of solar power exported is as good as 1 kWh consumed onsite, from a country-wide perspective. In fact, the former is better when power conversion losses and embodied carbon of battery manufacture are accounted for.

Much literature exists on the design, operation and profitability of battery systems in the renewable energy sector, yet little exists on the environmental benefits of such systems. Exceptions include Carbajales-Dale *et al.*'s aggregated industry-wide analysis [11] which explores how much storage can be built if all its embodied carbon must be offset by the wind and solar industries, and Fathima and Palanisamy's work [12] which optimizes a wind-PV-battery system in a Tamil Nadu context to minimize costs, and evaluates the resultant CO_2 emissions reductions.

It is implicit in many papers that renewable co-located storage batteries are not financially worthwhile unless also offering ancillary services to the grid. For example, Stroe *et al.* investigate the use of a $LiFePO_4$ battery in concert with a wind farm to deliver primary frequency response to the Danish grid [13]. Many studies ignore the renewable power installation entirely, instead analyzing the economics of a stand-alone battery offering frequency and reserve services to the grid as well as profiting from arbitrage [14], [15].

It appears that no papers considered it worth analyzing a renewable power system using storage solely for curtailment avoidance when expanding generation capacity beyond its given grid export limit. The novelty of this work is in doing just this: evaluating the CO_2 emissions reduction possible, and quantifying how badly loss-making such a scheme would be. Thus the scale of the challenge and the need for further technological improvement are elucidated.

The situation investigated in this work is the installation of a battery system at the site of a solar PV farm where grid export is severely limited. Section II explains the context, the battery operation strategy, and the simulations conducted to find the carbon-optimal battery size. Section III presents results and analysis of the carbon price required

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to subsidize such a strategy. Section IV discusses the implications, and suggestions for further work.

Nomenclature

P_{PV}	(kW)	Rated capacity of PV array
E_B	(kWh)	Battery capacity
E_{B*}	(kWh)	Carbon-optimal battery capacity
P_{conv}	(kW)	Power converter capacity
P_{conv*}	(kW)	Carbon-optimal power converter capacity
$P_{toGrid}(t)$	(kW)	Power exported to the grid across all N years
$P_{toGrid,n}(t)$	(kW)	Power exported to the grid in year n
$P_{gen}(t)$	(kW)	Power generated by PV
$P_{charge}(t)$	(kW)	Power to charge battery bank (<0 is discharge)
NPV	(£)	Net present value (discounted lifetime profit)
NPV_{CO2}	(kg)	Discounted lifetime CO_2 savings
Enow	(kWh)	Energy stored in battery when switching from day regime to night
exportP	(kW)	Set-point night-time discharge power

II. Method

A. Context

The situation modelled here is based on the Lymington array in Hampshire, UK, owned by West Solent Solar Co-operative [16]. The array size is 2.4 MW, and West Solent earns revenue in two ways: a Power Purchase Agreement (PPA) with an energy retailer which pays them a fixed price per kWh exported; and the Feed-in Tariff (FiT), a subsidy per kWh of generation claimed from the UK government [17]. The revenue is shared out yearly amongst the Co-operative members, who contributed towards the initial investment.

FiTs were designed to assist immature technologies that could help the country reach its carbon emissions reduction targets. The FiT level for each technology (large-scale PV, rooftop PV, onshore/offshore wind, etc.) is reduced every year, but an individual installation is guaranteed payment for its entire lifetime at the level locked on to when operations began (e.g. 7 p/kWh in 2014 [17], in the case of the Lymington array). Driven by the unexpectedly rapid development of renewable technologies, FiTs were re-assessed in 2016 and the level for large-scale solar PV (amongst others) was reduced dramatically [18]. As this work is intended to be forward-looking, and FiTs are unlikely to play much part in future UK scenarios, they are excluded from the following analysis.

Like all solar farms seeking to connect to the 11 kV primary distribution level, the Lymington array needed permission from the Distribution Network Operator (DNO). After assessing the work needed to cope with the added power injection (such as reinforcing power lines and upgrading transformers, to avoid breaching thermal or voltage limits), the DNO charged a connection fee to grant the Lymington array permission to export up to 2.0 MW to the grid [16]. In line with standard practice, 20 % more generation capacity was installed (2.4 MW) as the boost to winter-time generation outweighs the summer noon-time curtailment losses. A simulation estimates these losses to be 19 MWh, that is, 0.03% of 67 GWh generated over 25 years (see Figure II-1).

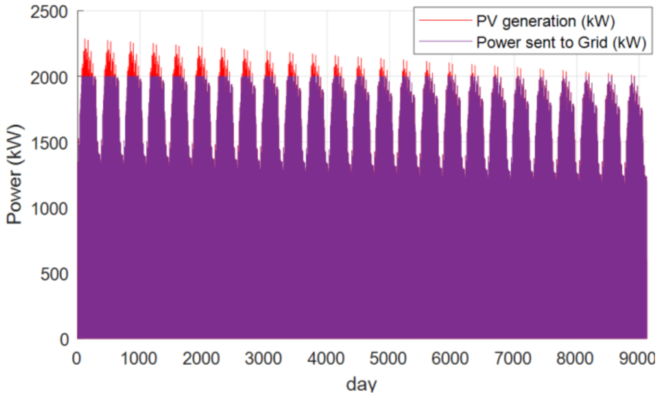

Figure II-1. PV generation input time series showing a typical year's data scaled to 2.4 MW, replicated 25 times, with PV degradation of 0.5 %/year.

This hypothetical investigation asks: supposing there were enough land and funds to expand the solar generation capacity further, to 3.0 MW, 3.5 MW, or 4.0 MW, what size of battery and converter would maximize the avoided carbon emissions, given the export limit of 2.0 MW?

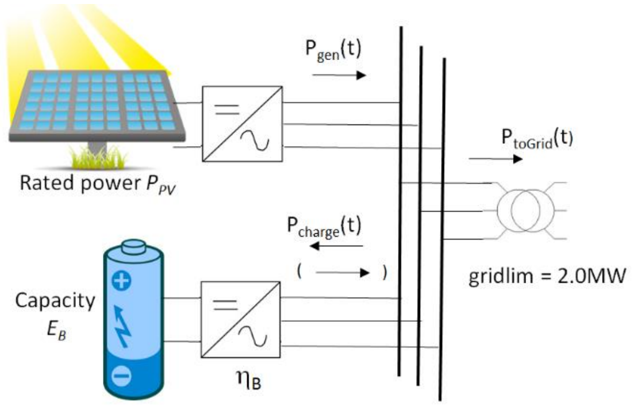

Figure II-2. Schematic of solar-and-battery farm. In fact there are many strings of PV panels and batteries connected in parallel to the 3-phase AC bus, but these are lumped together for simplicity. See Nomenclature.

B. Operation strategy: store-then-discharge

A Matlab model was written to simulate a PV farm feeding power into the grid up to a given export limit, where all excess power between 11am-6pm is used to charge a lithium-ion battery (limited by its allowed charge power and maximum charge capacity, curtailing any remaining power thereafter), and after 6pm the entire contents of the battery at that time (saved in the variable *Enow*) are then discharged into the grid over 14 hours (at a rate *exportP*). The control strategy is shown in Figure II-3. No claim is made to its optimality, but good practice to reduce battery losses is followed by keeping state of charge (SoC) between 10 % and 90 %, and discharging slowly [19].

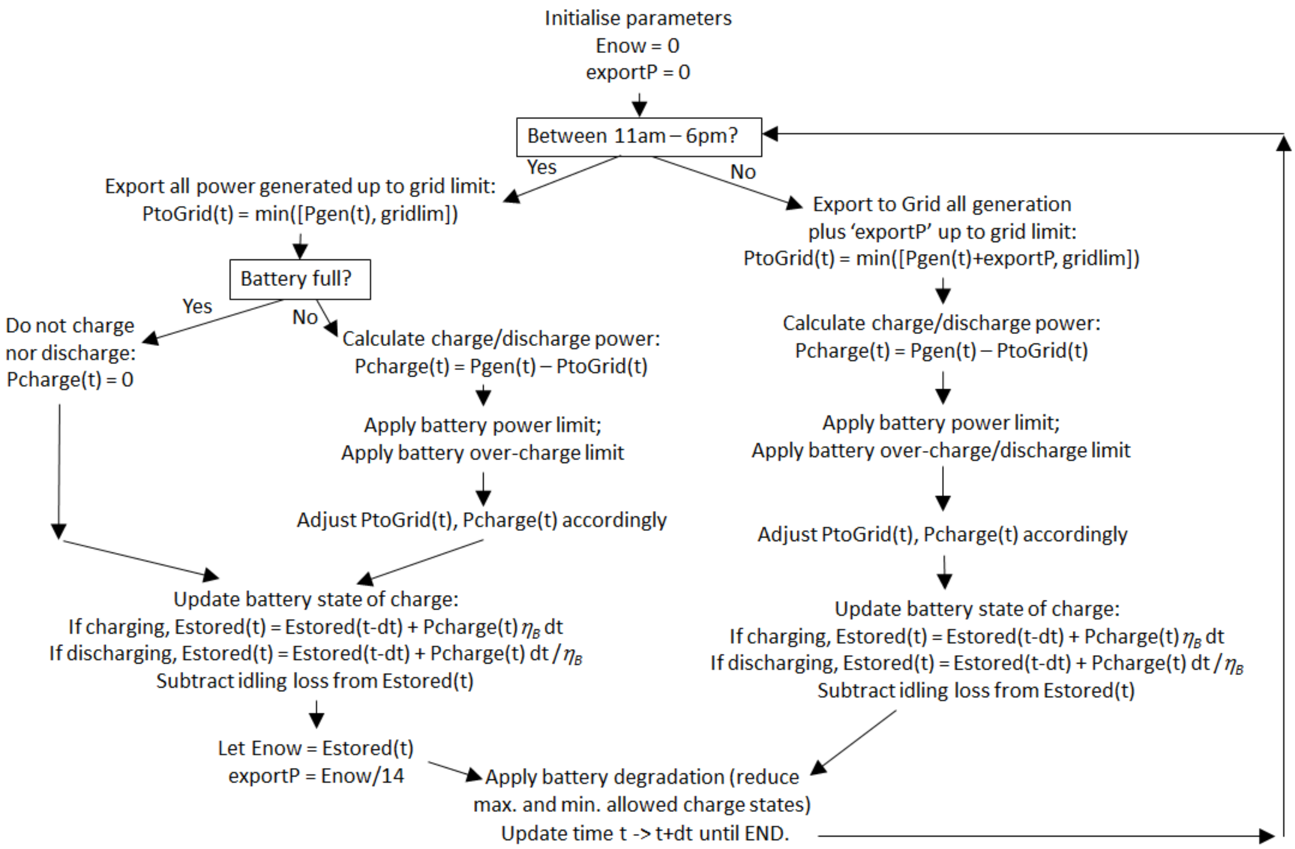

Figure II-3. 'Store-then-discharge' control strategy. See text above for explanation, including meanings of variables Enow, exportP, etc.

A single parameter η_B is used for the combined efficiency of the battery and its power converter, such that the AC-AC round-trip efficiency is η_B^2. This is an approximation, as the efficiency varies with charge/discharge rate, state of charge, temperature, power through the converter, and other factors.

The system operation is demonstrated in Figure II-4 with a 5.5 MWh / 1.1 MW battery (chosen for illustration purposes only). Note that the converter reaches its power limit around day = 165.5, and the battery reaches maximum charge (90 %) shortly after, showing curtailment by power limit and by energy limit that day.

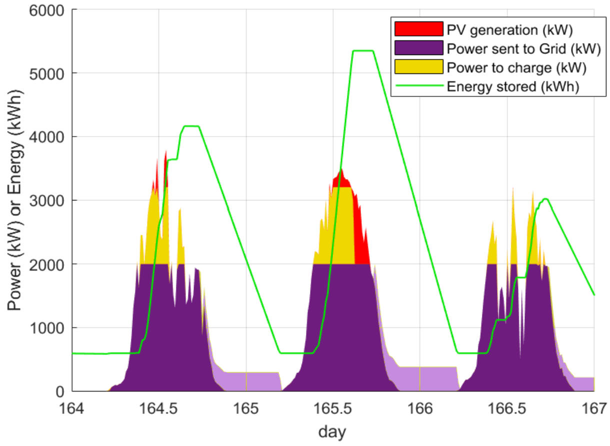

Figure II-4. Time series showing PV generation and battery operation.

C. *Input data and parameters*

A time series of PV power generation from Hill View Farm, Hampshire, UK, from 16 June 2016 to 16 June 2017 was used as input. Data were recorded at 15 minute intervals. Missing data were linearly interpolated over if the missing period was less than one hour. If more, the entire day was replaced with data from 7 days previously. The time series was replicated for 25 years, and a linear output power degradation of 0.5 %/year was applied [20]. The entire time series was linearly scaled to 2.4 MW, 3.0 MW, 3.5 MW and 4.0 MW.

Table II-1. Parameters used in subsequent simulations, with corresponding uncertainties. 'Error' values are used in the sensitivity analysis.

	Meaning	*Unit*	*Value*	*Error*
	PV parameters			
p_{PV}	Price	£/kW	1000 [21]	± 100
c_{PV}	Embodied CO_2	kg/kW	1800 [22]	± 300
-	Degradation rate	%/y	0.5 [20]	-
N	Lifetime	y	25	-
gridlim	Grid export limit	MW	2.0	-
	Battery parameters			
p_B	Price	£/kWh	400 [9]	-
c_B	Embodied CO_2	kg/kWh	80 [23]	± 20
-	Capacity degradation	%/10 y	20 [24]	-
-	Lifetime	y	10 [24]	-
n_B	Replacement years		{10,20}	-
e_B	Price escalation	%/y	-8 [25]	± 2
$e_{B,CO2}$	CO_2 intensity escalation	%/y	-8	± 2
-	Upper charge limit	%	90	-
-	Lower charge limit	%	10	-
η_B	Charge/discharge efficiency	%	93.2 [19], [26]	-
-	Idling loss	C-rate	0.000 05	-

Converter parameters				
p_{conv}	Price	£/kW	100 [16]	± 20
c_{conv}	Embodied CO_2	kg/kW	70 [27]	± 20
	Lifetime	y	10	-
n_{conv}	Replacement years		{10,20}	-
e_{conv}	Price escalation	%/y	-5 [9]	± 1
$e_{conv,CO2}$	CO_2 intensity escalation	%/y	-5	± 1
Financial parameters				
i	Inflation rate	%/y	2.5	-
r	Interest rate	%/y	4.0	-
p_{elec}	Electricity sale price	£/MWh	43 [28]	-
O&M%	Operations and Maintenance	%	1.0 [16]	-
CO_2 parameters				
i_{CO2}	CO_2 intensity rate of change	%/y	-1.5 [29]	-
r_{CO2}	CO_2 discount rate	%/y	1.5 [29]	-
c_{elec}	CO_2 intensity of grid electricity	kg/kWh	0.4 [30]	-

Embodied carbon of battery manufacture varies up to 60 % depending on the carbon intensity of energy at the location of manufacture – an average value for Chinese manufacture is used [23].

It is uncertain how the carbon intensity of manufacture of batteries and converters will change, so they are assumed to change in line with price – given that batteries were 240 kg/kWh three years ago, this is not unreasonable [31].

A lifetime of 10 years is used for both the battery and converter, guided by the Tesla Powerwall's warranty [24] and other sources [12]. In reality, the lifetime is affected by many aspects of the battery utilisation. Further, the expected distribution of lifetimes means separate packs or modules must be replaced over time, whereas an approximation is made here whereby the batteries are replaced all at once every 10 years.

The SoC limits are imposed to preserve battery life – they do not affect the degradation rate in this model, but are used as realistic standard practice [19].

The electricity sale price is constant across the day, typical of a power purchase agreement (PPA), assumed renewed yearly in line with inflation [28].

CO_2 intensity rate of change is the rate at which the economy (and therefore the rest of grid generation) is expected to de-carbonise [29].

CO_2 discount rate occupies the same role as (financial) interest rate r, but has different interpretations. CO_2 accumulates in the atmosphere such that a ton emitted today is as bad as a ton tomorrow (suggesting $r_{CO2} = 0$), but the more slowly CO_2 emissions are reduced today, the more quickly they must be reduced in future to avoid catastrophic climate change [32] (suggesting $r_{CO2} > 0$ %). r_{CO2} may also indicate how much one values the current population's welfare compared to future generations (high means currently existing people are preferred, low means the avoidance of future climate-driven suffering is preferred) [29].

CO_2 intensity of grid electricity is approximated as constant across each year, though in reality it varies throughout the day and year [30].

D. Equations

For each PV expansion considered (to 3.0, 3.5, 4.0 MW total), a range of battery capacities and power limits (effectively, converter capacities) were simulated. For each, the lifetime profit net present value (NPV) was calculated (with variables, parameters and parameter values given in *Nomenclature* and Table II-1):

$$\text{NPV} = \text{Electricity revenue} - (\text{Initial cost} + \text{Replacement costs} + \text{O \& M costs}) \quad (1)$$

where

$$\text{Electricity revenue} = \sum_{n=0}^{N-1}\left[p_{elec}\frac{(1+i)^n}{(1+r)^n}\sum_t P_{toGrid,n}(t)\,\mathrm{d}t\right] \quad (2)$$

$$\text{Initial cost} = p_{PV}\cdot P_{PV} + p_B\cdot E_B + p_{conv}\cdot P_{conv} \quad (3)$$

$$\text{Replacement cost} = p_B\cdot E_B\sum_{nB}\frac{(1+i+e_B)^{nB}}{(1+r)^{nB}} + p_{conv}\cdot P_{conv}\sum_{nconv}\frac{(1+i+e_{conv})^{nconv}}{(1+r)^{nconv}} \quad (4)$$

$$\text{O \& M (operations and maintenance) costs} = \sum_{n=0}^{N-1}\text{Initial cost}\cdot\text{O\&M\%}\cdot\frac{(1+i)^n}{(1+r)^n} \quad (5)$$

An analogous expression is used to calculate the lifetime CO_2 savings:

$$\text{NPV}_{CO2} = CO_2\text{ savings} - (\text{Initial embodied }CO_2 + \text{Embodied }CO_2\text{ of Replacements}) \quad (6)$$

where

$$CO_2\text{ savings (by displacing fossil fuel generation)} = \sum_{n=0}^{N-1}\left[c_{elec}\frac{(1+i_{CO2})^n}{(1+r_{CO2})^n}\sum_t P_{toGrid,n}(t)\,\mathrm{d}t\right] \quad (7)$$

$$\text{Initial embodied }CO_2 = c_{PV}\cdot P_{PV} + c_B\cdot E_B + c_{conv}\cdot P_{conv} \quad (8)$$

$$\text{Embodied }CO_2\text{ of replacements} = c_B\cdot E_B\sum_{nB}\frac{(1+i_{CO2}+e_{B,CO2})^{nB}}{(1+r_{CO2})^{nB}} + c_{conv}\cdot P_{conv}\sum_{nconv}\frac{(1+i_{CO2}+e_{conv,CO2})^{nconv}}{(1+r_{CO2})^{nconv}} \quad (9)$$

The CO_2 emitted by operations and maintenance is neglected. It would involve a technician driving to the site a few times a year, which only becomes significant if the site is extremely remote. It should be noted that CO_2 is not the only problematic emission: a similar calculation could be conducted for NO_x, SO_x, heavy metals, or other pollutants or toxins associated with the manufacture of PV panels, batteries and converters, and the operation of fossil-fuelled generation plants. But as more data on embodied carbon is available, carbon emissions reduction is the objective here.

III. RESULTS

A. Battery/Converter Optimization

The base case against which all others are compared is 2.4 MW rated PV power, no battery. This case saves the emission of 14.44 kton CO_2 over its lifetime, but makes a loss of £494 000 if the feed-in tariff is neglected. (It was roughly 7 p/kWh at the time the Lymington array began operation – this would result in a lifetime NPV (profit) of £2.5 million for capital expenditure of £2.6 million [16]. As the feed-in tariff is now nearly zero for large solar farms, it is neglected in the following work.

Note that the results for each PV expansion plan (to 3.0, 3.5, 4.0 MW total) with batteries are not compared to the same cases without batteries – this is because without batteries, the energy curtailed would be so enormous as to damage the PV panels and their inverters through heat degradation, so such expansions would never be conducted without batteries. This is why 2.4 MW / no battery is the base case. There is still some curtailment even with batteries, and this is commented on below.

Let us define $\Delta NPV(P_{PV})$, the differential NPV for a system with P_{PV} solar capacity,

$$\Delta NPV(P_{PV}) = NPV(P_{PV}) - NPV(2.4\text{ MW}) \qquad (10)$$

where NPV(2.4 MW) is the NPV of the 2.4 MW / no battery base case, and similarly for the differential carbon savings,

$$\Delta NPV_{CO2}(P_{PV}) = NPV_{CO2}(P_{PV}) - NPV(2.4\text{ MW}) \qquad (11)$$

For each PV expansion plan, the battery capacity and power which maximise the lifetime CO_2 savings relative to the base case, ΔNPV_{CO2}, are found by a directed search, as in Figure III-1.

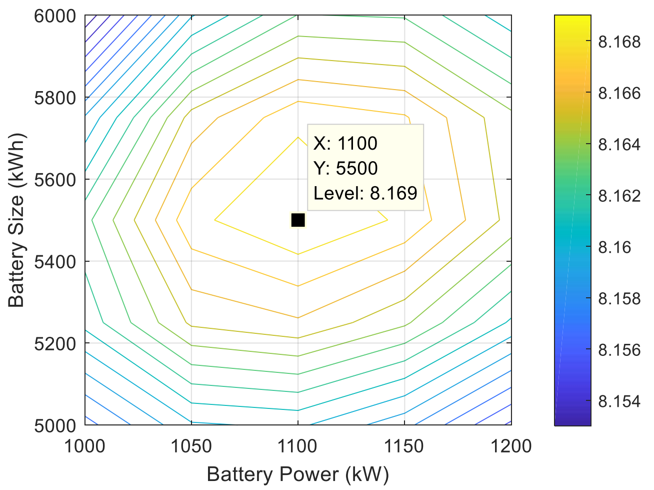

Figure III-1. Lifetime CO_2 savings relative to base case (ΔNPV_{CO2}, in kton), for P_{PV} = 4.0 MW.

Table III-1. Battery and converter capacities that maximize lifetime CO_2 savings (compared to base case 14.44 kton) for three PV expansion plans.

	P_{PV} (MW) 3.0	3.5	4.0
$E_{B\star}$ (MWh)	0.95	3.0	5.5
$P_{conv\star}$ (MW)	0.3	0.7	1.1
ΔNPV (million £)	- 0.866	- 2.506	- 4.467
$\Delta NPV_{CO2\star}$ (kton)	3.29	5.79	8.17

B. CO_2 price vs. Battery price and PV expansion

The carbon price, $p_{CO2}(P_{PV})$, is here defined as:

$$p_{CO2}(P_{PV}) = -\Delta NPV_{\star}(P_{PV}) \,/\, \Delta NPV_{CO2\star}(P_{PV}) \qquad (12)$$

It is the ratio of the extra whole-life financial loss, to the extra lifetime CO_2 savings for the optimized system with P_{PV} rated power relative to the 2.4 MW / no battery base case. It represents the price that must be put on each ton of CO_2 emitted in order for the CO_2-optimized case to make the same profit (or incur the same loss) as the base case. This carbon price may take the form of a tax on fossil fuel-generated electricity, raising its market price, or a direct subsidy to the solar farm. In either case, it is equivalent to an increment to the electricity sale price. For example, a carbon price of £200/ton would translate to roughly

£200/ton × 0.4 ton/MWh = £80/MWh, or 8 p/kWh,

not far off the feed-in tariff level of 7 p/kWh at which the Lymington array locked in when it began operation.

For context, the EU Emissions Trading Scheme (ETS) settled on carbon prices between €3/ton - €9/ton (roughly £3/ton - £8/ton) over 2013 - 2015 by its cap-and-trade mechanism [33], while the World Bank recommends a carbon price of \$40/ton - \$80/ton (£30/ton - £60/ton) in order to keep the global temperature rise within 2°C above pre-industrial levels [34]. This would suggest that the UK solar feed-in tariff (equivalent to roughly £150/ton before the steep reduction in 2016 [17]) was over-generous, even by environmentalists' standards.

The required carbon price was calculated for the systems with battery/converter sized to optimize CO_2 savings, for initial battery prices £400/kWh, £300/kWh, £200/kWh, £100/kWh, £50/kWh. This is shown in Figure III-2, along with the corresponding lifetime losses for these systems. These results are summarized in Table III-2.

The greater the PV expansion, the larger the batteries and converters needed, the greater the financial loss incurred, therefore the greater the carbon price needed to subsidize such an option.

Another interpretation of the carbon price is as a metric to help policy-makers decide how best to incentivize carbon-cutting technology. For example, if there is an option that saves CO_2 emissions for less than £264/ton, it should be taken before considering expanding the solar farm to 3.0 MW and installing a 0.95 MWh / 0.3 MW

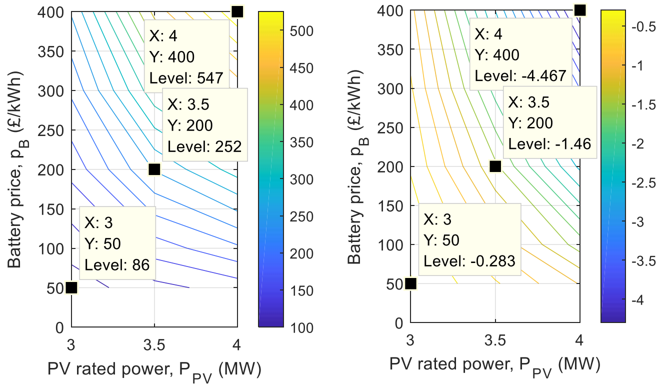

Figure III-2. Left: required carbon price p_{CO2} (£/ton) to subsidise CO_2-optimal systems at different battery price points and PV expansion plans. Right: ΔNPV (differential loss across lifetime, in millions £) for CO_2-optimal systems at different battery price points and PV expansion plans.

Table III-2. Additional losses and carbon prices for different PV expansion plans and battery prices.

	Battery price, p_B (£/kWh)	P_{PV} (MW) 3.0	3.5	4.0
$\Delta NPV_*(P_{PV})$, $p_{CO2}(P_{PV})$	400	-£866 k, £264/ton	-£2.506 m, £433/ton	-£4.467 m, £547/ton
	300	-£675 k, £213/ton	-£1.983 m, £343/ton	-£3.508 m, £430/ton
	200	-£519 k, £163/ton	-£1.460 m, £252/ton	-£2.550 m, £312/ton
	100	-£362 k, £113/ton	-£938 k, £162/ton	-£1.592 m, £195/ton
	50	-£283 k, £87/ton	-£676 k, £117/ton	-£1.113 m, £136/ton

battery (at £400/kWh). Such an option could be to subsidize the installation of another solar farm elsewhere. To cancel the £494 000 loss (see Section III.A) of a 2.4 MW solar farm without battery would require at least

$$\frac{£494\,000}{(2.4\text{ MW} \times 11\%\text{ load factor} \times 8760\text{ hour/year} \times 25\text{ years})} = £8.54/\text{MWh, or } 0.854\text{ p/kWh}$$

in subsidy, or an equivalent carbon price of

$$£8.54/\text{MWh} / 0.4\text{ ton/MWh} = £21.36/\text{ton}.$$

These figures are very rough and do not account for interest, inflation, tax, shareholder payments, etc. Even including those they are still likely to be considerably less than the figures in Table III-2.

The required carbon price to subsidise the solar-and-battery options tabulated above all exceed £87/ton, even for a battery price reduction to £50/kWh. The optimal price point is no battery in every case. Such prices are unlikely to be reached by lithium-ion batteries for at least two decades [25].

The only currently existing energy storage that can reach costs cheaper than £100/kWh is pumped hydroelectric – but its application is limited by geography. Lead-acid batteries do not have this restriction and reach similar prices, but have similarly low round-trip efficiency (around 75 %, compared to 87 % used in the above work). The lifetime of lead-acid is also less favorable compared to lithium-ion, around 1000 cycles compared to 10 000 [35].

The energy curtailed is calculated as

$$\sum_t P_{gen}(t) - P_{toGrid}(t)\ dt$$

which, as a percentage of the total power $\sum_t P_{toGrid}(t)\ dt$ exported over 25 years, is roughly 0.7 % for the expansion to 3.0 MW, 1.3 % to 3.5 MW and 2.0 % to 4.0 MW. The curtailment is less for larger batteries and more powerful converters. These figures are substantially more than the 0.03 % curtailment for the 2.4 MW / no battery base case, but typically 2-4 times less than the amount curtailed for those sizes of PV capacity without batteries. It is beyond the scope of this analysis to comment on what level of curtailment causes unacceptable thermal damage to the system.

C. *Sensitivity Analysis*

The required carbon price was re-calculated under an optimistic and a pessimistic scenario. For the optimistic scenario, lower-bound values (Table II-1) were used for the price and embodied carbon of PV, battery and converter, and escalation rates for price and embodied carbon of battery and converter; upper-bound values were used for the pessimistic scenario.

Table III-3. Required carbon price (lower and upper bounds) to subsidize PV expansion with batteries, given different battery prices.

	Battery price, p_B (£/kWh)	P_{PV} (MW) 3.0	3.5	4.0
$p_{CO2}(P_{PV})$ (£/ton)	400	208 333	350 543	444 686
	300	165 274	273 435	344 545
	200	121 215	195 327	244 403
	100	77 155	117 219	144 261
	50	55 126	79 165	94 191

There is considerable uncertainty in the required carbon price thus calculated. The neutral scenario (Table III-2) was explored further by reducing the battery capacity by 10 % (Table III-4) - the impact on carbon savings was small compared to the reduction in investment costs, leading to an almost proportional reduction in the required carbon price. However, as noted above, a smaller battery capacity leads to marginally more curtailment and thermal damage.

Table III-4. Battery and converter capacities that maximize lifetime CO_2 savings (compared to base case 14.44 kton) for three PV expansion plans, compared to cases with battery capacity reduced by 10 % .

	P_{PV} (MW)		
	3.0	***3.5***	***4.0***
E_{B*} (MWh)	0.95	3.0	5.5
0.9 E_{B*} (MWh)	0.855	2.7	4.95
P_{conv*} (MW)	0.3	0.7	1.1
ΔNPV (million £) for E_{B*}	- 0.866	- 2.506	- 4.467
and 0.9 E_{B*}	- 0.802	- 2.301	- 4.092
ΔNPV_{CO2*} (kton) for E_{B*}	3.29	5.79	8.17
and 0.9 E_{B*}	3.29	5.78	8.16
$p_{CO2}(P_{PV})$ (£/ton) for E_{B*}	264	433	547
and 0.9 E_{B*}	244	398	501

Even with all the uncertainties, it is clear that the operation strategy described in this work is uneconomical unless:

a) An international carbon price well in excess of the World Bank's £60/ton recommendation is imposed

b) Electricity sale price increase equivalently (from the £43/MWh used here to well above £80/MWh) due to other factors, such as increased demand or unexpected reduction in the supply of fossil fuels

c) The cost of energy storage decreases dramatically, to below £50/kWh

d) The strategy is augmented by offering other services to the grid, such as frequency response, voltage regulation, etc.

The probability of a) and b) are beyond the scope of this work to predict. Options c) and d) are amenable to technological progress, but must be deferred to future work.

IV. Discussion

A simple store-then-discharge curtailment avoidance strategy was found insufficiently profitable. This is in contrast to Fathima and Palanisamy [12] who find significant carbon savings are possible and profitable for a range of battery types – this is largely explicable by the greater cost and carbon intensity of the fossil fuel alternative in Tamil Nadu, namely diesel, compared to the fuel mix of the UK grid. For a UK context, strategies beyond store-then-discharge must be explored. However, the publications doing so [14], [15] focus on maximizing profit while neglecting to quantify the environmental benefits. Though many uncertainties exist in the literature on carbon accounting (life cycle analyses of PV [22], batteries [23] and especially power electronics [27]), it seems remiss to ignore this aspect of system design.

Further work on an improved value proposition should include considerations of:

- Balancing requirements for stored energy head-room and foot-room (so that services can be fulfilled if called upon) with charging to absorb excess generation
- Additional degradation caused by offering ancillary services, and the effect on battery lifetime and therefore costs associated with the replacement schedule
- Distributed failure of separate battery modules, requiring replacement one at a time rather than all at once as modelled here
- Time-dependent carbon intensity of electricity production – in a hypothetical country heavily dependent on solar power (where electricity would be very low-carbon during the day and more carbon-intense during the night – the reverse of the UK [30]), even more carbon savings can be achieved even by this simple store-then-discharge strategy – but carbon emissions would still need to be priced appropriately.

In addition to drawing more revenue by offering ancillary services, it may still be necessary to explore less costly options for battery supply. One such that receives much attention is the second-life battery: an electric vehicle battery which has degraded until its energy density and power density are no longer sufficient for mobile applications, but still good enough for stationary applications [36], [37].

Future work pursuing this avenue must consider:

- The expected price of second-life batteries, given the turnover of EVs
- The expected 'second lifetime' of the second-life batteries
- How the degradation imposed by the 'first life' may affect performance in the second life
- At what point (after how much degradation) the risk of sudden failure becomes too great.

V. Conclusions

An analysis has been presented of a solar farm with co-located battery system, the battery allowing storage and time-shifted sale of energy that would otherwise have been curtailed due to the grid export limit imposed by the DNO.

It was found that the carbon-optimal battery/converter sizes could not return a profit unless heavily subsidized, even if the price of energy storage were to reduce to less than an eighth of current prices. Such subsidy is not recommended as long as more profitable de-carbonization options exist.

While much literature exists on the design, operation and profitability of battery systems in the renewable energy sector, little exists on the environmental benefits of such systems. This work attempts to fill some of that niche, but much is still left to be done: having shown that a simple store-then-discharge strategy is not profitable enough, a strategy incorporating ancillary service provision additionally to curtailment avoidance must be developed, building on existing profit-maximizing strategies. The analysis must also consider the effects of the operation strategy on battery degradation, therefore on lifetime and replacement costs, and the option of using second-life batteries rather than brand new.

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