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Short-run impact of electricity storage on CO_2 emissions in power systems with high penetrations of wind power: A case-study of Ireland

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Abstract

This article studies the impact on CO_2 emissions of electrical storage systems in power systems with high penetrations of wind generation. Using the Irish All-Island power system as a case-study, data on the observed dispatch of each large generator for the years 2008 to 2012 was used to estimate a marginal emissions factor of 0.547 $kgCO_2/kWh$. Selected storage operation scenarios were used to estimate storage emissions factors – the carbon emissions impact associated with each unit of storage energy used. The results show that carbon emissions increase in the short-run for all storage technologies when consistently operated in 'peak shaving and trough filling' modes, and indicate that this should also be true for the GB and US power systems. Carbon emissions increase when storage is operated in 'wind balancing' mode, but reduce when storage is operated to reduce wind power curtailment, as in this case wind power operates on the margin. For power systems where wind is curtailed to maintain system stability, the results show that energy storage technologies that provide synthetic inertia achieve considerably greater carbon reductions. The results highlight a tension for policy makers and investors in storage, as scenarios based on the operation of storage for economic gains increase emissions, while those that decrease emissions are unlikely to be economically favourable. While some scenarios indicate storage increases emissions in the short-run, these should be considered alongside long-run assessments, which indicate that energy storage is essential to the secure operation of a fossil fuel-free grid.

Keywords

Wind power, energy storage, carbon dioxide, greenhouse gas emissions, marginal, environmental impact, electricity

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Introduction

To address the problem of anthropogenic climate change,[1] governments have set deep and binding carbon reduction targets,[2,3] which in turn will require the almost complete decarbonisation of electricity generation within relatively short timescales.[4] Studies that detail the potential pathways to such low-carbon futures are characterised by the considerable changes required to how electricity is generated, distributed and used.[5–8]

Low-carbon generation portfolios consisting of nuclear, renewables, and carbon capture and storage have particular challenges associated with the task of matching electricity supply and demand, with the prospect of increasingly volatile and even negative wholesale electricity prices.[9] Studies that investigate in detail the system balancing requirements of such futures are characterised by a requirement for large-scale deployment of electricity storage.[10–13]

In these scenarios, storage is a means to an end – the ultimate goal being a low-carbon future. The implied environmental impact of storage in these scenarios is positive, as it enables greater penetrations of renewables, displacing more fossil-fuel generation than would be the case without it. Most power systems today, however, are not low-carbon and are still dominated by fossil-fuel generation.[14] The environmental case for adding electricity storage to existing power systems is not straightforward, even for those with relatively high penetrations of renewables. This is because energy losses associated with storage may well increase fossil-fuel generation and emissions, depending on how the storage is operated.

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There is, as a result, a need for assessments of the short-run environmental impact of storage, which can be balanced with long-run impact assessments to support the overall life-cycle environmental impact assessment. Here, short-run refers to there being negligible structural change to the electricity system being analysed, while long-run explicitly takes into account structural changes, i.e. how the intervention affects the merit-order, and power station commissioning and decommissioning.[15] When combined with corresponding economic impact assessments, environmental impact assessments can provide the necessary support for evidence-based policy and investment decision-making regarding electricity storage.

This article aims to estimate the short-run environmental impact of electricity storage in current power systems, and those with high penetrations of wind power. The article focuses on in-use impacts of grid-connected storage on CO_2 emissions at the national electricity system level due to the effect the storage will have on marginal generation. Environmental impacts associated with production, maintenance and disposal of storage systems are not included. A variety of storage operational scenarios are considered, including the case where storage is used to avoid curtailment of wind power. Emissions factors are estimated for the scenarios, in terms of $kgCO_2$ per kWh of electricity stored, for a variety of storage round-trip efficiencies. These estimates are based in turn on estimates of the marginal emissions factors of the Irish All-Island power system, which consists of the interconnected transmissions systems of the Republic of Ireland and Northern Ireland. The All-Island system makes a useful real-world case study because of its already high penetrations of wind power, ambitious targets to increase wind penetration further and existing levels of wind curtailment to maintain system stability.[16,17] Marginal emissions factors for the All-Island power system are estimated from regression analysis of data of the observed dispatch of generators for the years 2008 to 2012. This method has the principal advantage of circumventing the need for any of the assumptions about generator merit-order that tend to underpin alternative approaches, such as full time-series simulation of economic dispatch of generation and storage. The method is readily applicable to other power systems, provided similar underlying data are available.

Literature review

The economics of storage in power systems with high penetrations of renewable energy

By studying the environmental impact of storage, this article supports research into the economic viability of electricity storage in power systems, particularly those where storage is associated with the integration of renewables. Often such studies evaluate the financial benefit to a storage operator of pursuing energy arbitrage in wholesale electricity markets,[18–22] buying electricity to charge storage when wholesale electricity prices are low, and discharging storage to sell electricity when prices are high. This is intended to represent how storage systems would operate in today's markets, i.e. in a manner that seeks to maximise profits for the storage operator. In markets with high penetrations of renewables, output from renewables can be expected to be inversely correlated with wholesale electricity prices.[9] In such scenarios, operating storage in a profit-maximising arbitrage manner can therefore also result in a positive environmental impact, provided a sufficient amount of renewable energy that would otherwise have been wasted is used, and that this outweighs any potential increases in emissions due to storage losses, together with production and disposal of the storage equipment itself.

While these studies examine the economic case for storage, the important point is that a consideration of the environmental impacts is out of scope, or a positive environmental impact might be implied or assumed. However, without backing up these studies with corresponding environmental evaluations, there is a risk of investment that was intended to fund low-carbon projects being directed to projects that might actually make the environmental situation worse. This article therefore focusses on the environmental impact of storage used for system balancing in an electricity arbitrage manner, under the assumption that this is the primary intended role for storage in power systems. The present study therefore covers the impact of storage operated over time-scales greater than a half-hour, though we acknowledge it can also have a role over shorter time-scales.[23,24]

Life cycle assessments of specific storage technologies

Life cycle assessments evaluate the impact of a technology on the environment associated with its full life cycle, including extraction and transportation of raw materials, manufacturing, use and eventual recycling and disposal. Because of differences in evaluation methods, assessments often fall into one of two categories: those that focus on evaluating the impact of the use-phase of the technology and those that focus on the other steps in the cycle – sometimes referred to as production or 'cradle to gate' assessments. Batteries, for example, are a storage technology attracting attention, in part due to the potentially large adoption of electric vehicles in low-carbon scenarios.[6] Production impact assessments of various types of batteries, however, demonstrate the high environmental costs associated with their manufacture, production, disposal, etc. and thus their potential to have a detrimental overall impact.[25,26]

There is a wide variety of competing storage technologies[27,28] with a correspondingly wide variety of

environmental impacts associated with their production. We adopt a technology agnostic approach, effectively treating storage as a 'black box' and analysing the impact it can be expected to have when connected and operated within a power system. The results are therefore applicable to any storage technology that can be connected to the grid and operated for the purposes of energy arbitrage. Our work therefore complements the literature on production impact assessment of storage technologies.

Allocating emissions to storage usage

Storage added to the grid can be expected to have two effects. First, total electricity demand will increase due to losses associated with the storage round-trip efficiency. Second, it will have an impact on the shape of the electricity demand profile, increasing demand while it charges and decreasing demand while it discharges. Both the increase in overall demand, and the change in the demand profile, will have an effect on the generators that are connected to the grid, and it is the resulting change in the emissions associated with these generators that constitutes the in-use environmental impact of the storage. In the long-run, the storage can also have a structural impact, e.g. by avoiding the need to build new peaking plant. In-use impact assessments can therefore be broken down into those that focus on short-run effects and those that focus on the long-run – here we focus on short-run effects.

Yang sets out a framework that describes different options for estimating and allocating emissions from electricity generation to electric vehicle charging, which can be appropriately applied for electricity storage technologies in general.[29] Regarding the quantification of the emissions impact of adding (or removing) electricity storage to the grid, in this article we adopt a temporally explicit marginal approach. Temporally explicit approaches are more accurate than aggregated approaches, as the latter fails to take into account the temporal variability of the storage operation and the impact this will have on electricity generation. A marginal approach is used here to estimate the impact of a change in electricity demand that will be met by the generators that are operating on the margin, and not the average of all the generators. This is a particularly important point, as renewables such as wind and solar have very low marginal costs and are not, therefore, generally operated on the margin. Arguments to use storage to 'balance wind power' and effectively turn it into baseload[30–32] may well be misguided, therefore, if grid-connected intermittent renewables are in fact the last to be stored, as argued by Swift-Hook.[33]

Yang makes an additional distinction between prospective and retrospective approaches. A retrospective approach relies on historic empirical data on the electricity system to estimate how it responds to changes and is appropriate for short-run impact analyses. A prospective approach makes assumptions about future scenarios, and forecasts impacts into the future, generally using power system dispatch models. These are necessarily more speculative, but appropriate for long-run impact assessments where structural changes to the system are factored in.

Estimating short-run marginal emissions factors

Hawkes developed an approach to estimate marginal emissions factors for national electricity systems based on the observed behaviour of generators.[34] Using detailed high-resolution information about the output of every large generator connected to the GB power system, the marginal emissions factor was estimated to be 0.69 $kgCO_2/kWh$ for the years 2002–2009. The average emissions factor for the same period was 0.51 $kgCO_2/kWh$, which if used instead of the marginal emissions factor could result in a significant misrepresentation of the impact of a policy intervention, highlighting the importance of maintaining empirically based estimates of marginal emissions factors to inform policy. Silar-Evans, Azevedo and Morgan apply the same technique to estimate marginal emissions factors for the US electricity system.[35] This article applies the same method to the Irish power system and builds also on previous studies that have focussed on estimating the impact of wind power on carbon emissions in Ireland.[36,37]

This article therefore adopts a temporally explicit marginal short-run approach to estimate the in-use impact of storage in the Irish All-Island power system. Similar approaches have been used to estimate the impact of electric vehicles in Australian power systems,[38] bulk electricity storage in the Texas power system[39] and lead-acid batteries in Great Britain's power system.[40] All studies found that storage could have a negative environmental impact and emphasised a possible trade-off between operating storage for private benefits (i.e. maximising profit) rather than social benefits (i.e. lowering emissions). In related work, Tuohy and O'Malley use a unit commitment and dispatch model (a prospective, not retrospective approach) to estimate the impact of pumped storage in power systems with high penetrations of wind power, basing the analysis on the Irish power system.[41] They found pumped storage not to be economically viable until very high penetrations of wind power were reached (above 50% of demand met by wind power), and furthermore that storage increased carbon emissions at wind penetrations below 60%.

Method and results

Average and marginal emissions factors for the All-Island power system

The method used to estimate marginal emissions factors is based on that developed by Hawkes.

Half-hourly metered generation for every generating unit in the All-Island power system for the years 2008–2012 was obtained from SEMO, the Single Electricity Market Operator (www.sem-o.com). This was used to create half-hourly data of generation by fuel type. Average emissions factors for each fuel type were then estimated. Total verified emissions for the major generating units in Ireland for the years 2008–2012 were determined from the EU Emissions Trading Scheme 'Allocations to Stationary Installations' tables (http://ec.europa.eu/environment/ets/). These were combined with total metered generation for the same units to obtain a weighted average emissions factor for the different fuel types, shown in Table 1. Half-hourly emissions by fuel type were then calculated. Renewables such as wind, hydro and biomass were allocated zero emissions, though we note that biomass can have quite a considerable environmental footprint.[42]

The resulting total emissions per year are checked against official values in Table 2. On average, our values are higher than official values by 2.6%. Our estimates for average emissions factors for the All-Island power system are checked with official values in Table 3. Our values underestimate for the years 2008–2010, and overestimate for the subsequent years, with an average error of −2.4%. This is a reasonable level of accuracy given the relative simplicity and transparency of the emissions allocation method compared with the complex methods used for official purposes, and acceptable given that the aim of the study is to estimate changes in emissions rather than absolute values.

Table 1. Estimates of average emissions factors ($kgCO_2$/kWh) by fuel-type for the Irish All-Island system.

Generator type	2008	2009	2010	2011	2012
Peat	1.13	1.14	1.11	1.10	1.11
Gas	0.40	0.40	0.40	0.40	0.41
Multi-fuel	0.40	0.40	0.41	0.40	0.40
Coal	0.91	0.92	1.00	0.95	0.95
Oil (fuel oil)	0.85	0.74	0.92	0.97	1.14
Distillate (gas/diesel oil)	0.91	0.87	0.84	0.86	0.87
Wind, hydro, biomass	0	0	0	0	0

Table 2. Comparison of our estimates of total yearly CO_2 emissions for Republic of Ireland against official and other published estimates.

	2008	2009	2010	2011	2012
EU Greenhouse Gas Inventories, Annex 1.5[a]	13,704	12,382	12,687	11,254	–
Di Cosmo & Valeri[36]	14,005	12,466	12,745	11,420	–
Our estimates	14,284	12,394	12,879	11,793	12,626

[a]http://www.eea.europa.eu/publications/european-union-greenhouse-gas-inventory-2012/annex-1.5-crf-tables-energy/view

Figure 1 shows an example January week for the All-Island power system. Figure 1(a) illustrates the net demand and estimated system emissions at half-hour resolution, Figure 1(b) shows the wind output and pumped hydro operation for the same week. The net demand in this case is defined as the sum of the total generation minus output from wind and hydro (excluding pumped hydro). Pumped hydro appears as negative metered generation when it is pumping, and these values were therefore not included in the net demand sum. To calculate the marginal emissions factor, we first calculate the change in net demand and emissions from one half-hour period to the next to obtain the change in net demand and the change in emissions as shown in Figure 1(c). It can be seen that these derived variables are highly correlated, and it is due to this property that a linear regression between them can then be performed to obtain an estimate of the marginal emissions factor.

Figure 2 shows the result of the linear regression between change in net demand and change in emissions for every half-hour period 2008 to 2012. Positive changes in demand go out to approximately 300 MWh/hh (half-hour), while negative changes go down to approximately 200 MWh/hh, reflecting the asymmetric gradients in net demand shown in Figure 1. The slope of the line provides the estimate for the average marginal emissions factor for the All-Island power system for these years, which is 0.547 $kgCO_2$/kWh. The R^2 coefficient is 0.941 which is sufficiently high to indicate a good fit and which is comparable to the fit of 0.95 reported for the same method applied to the GB power system.[34] The average emissions factor for the All-Island system for the same period is 0.489 $kgCO_2$/kWh, which is 11.9% lower than the marginal emissions factor. This indicates the scope for misallocation of emissions if the incorrect value is used in an impact assessment.

Estimating emissions factors for storage

The previous estimate of the marginal emissions factor shows a useful generalised result, which can

Table 3. Comparison of our estimates against official values for average emissions factor for electricity for the All-Island power system.

	2008	2009	2010	2011	2012
All-Island Fuel Mix Disclosure[a]	0.53	0.50	0.52	0.47	0.48
Our estimates	0.49	0.47	0.49	0.48	0.52
Difference	−8.9%	−6.2%	−6.9%	2.0%	7.8%

[a]http://www.allislandproject.org/

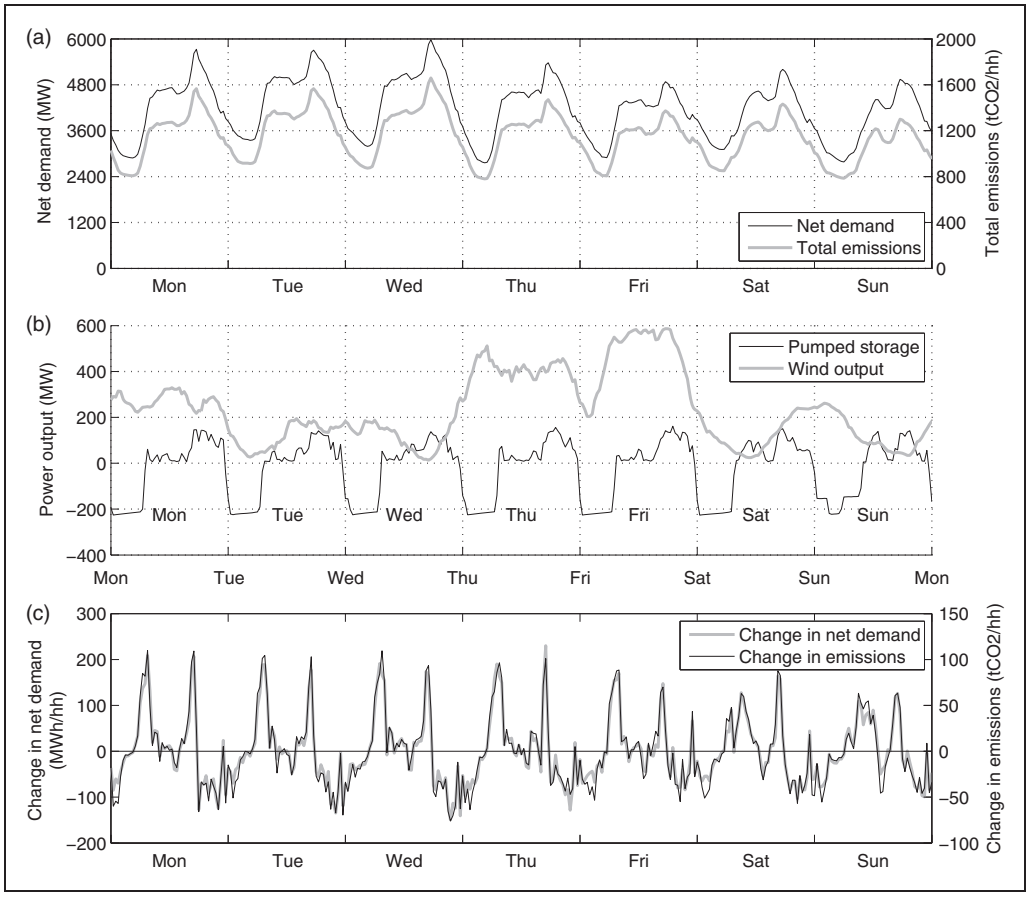

Figure 1. Net demand, system emissions, selected generation and the derived variables used to estimate the marginal emissions factor (change in net demand and change in emissions). "hh" stands for half-hour. The data are from one whole week in January.

be used to estimate the short-run impact of a change in electricity demand that is spread uniformly in time through each day and on all days, for example replacing old inefficient fridges with newer more efficient ones. Marginal emissions factors, however, are variable, and as storage operation is generally time-variable also, it is important to capture this variability for an accurate estimate of the impact of storage. The critical factor to account for is the difference in marginal emissions factor between when the storage is charging and when it is discharging. The overall storage emissions factor ($\epsilon_{storage}$) is dependent on the marginal emissions factors during charging (ϵ_{charge}) and discharging ($\epsilon_{discharge}$), and the storage round-trip efficiency ($\eta_{storage}$) as in equation (1).

$$\epsilon_{storage} = \epsilon_{charge} - \epsilon_{discharge}\eta_{storage} \quad (1)$$

Dividing through by the charging emissions factor provides a normalised form of the relationship, as in equation (2), which is shown graphically in Figure 3. The normalised storage emissions factor is shown on the y-axis, where a positive value indicates an increase in overall emissions and is of course not desirable. This is shown to be a function of the ratio of discharging and charging emissions factors, as well as the storage round-trip efficiency. To achieve a reduction in emissions, the storage needs to be operated such that the marginal emissions factor during discharging is greater than the marginal emissions factor during charging by a factor that is proportional to the losses incurred in the storage.

$$\frac{\epsilon_{storage}}{\epsilon_{charge}} = 1 - \frac{\epsilon_{discharge}}{\epsilon_{charge}}\eta_{storage} \quad (2)$$

Storage emissions factors for various operating scenarios

Seven storage operation scenarios are considered. The first considers storage operated at random which, when aggregated over time or many individual storage systems, is equivalent to a uniform increase in electricity demand that is proportional to the storage round-trip losses. While this is a somewhat unrealistic example of storage operation, it provides a base-case and comparison for the subsequent more realistic scenarios.

The second scenario is based on the common operating pattern for storage of 'peak shaving and trough filling' – the storage is discharged during periods of peak demand, and charged during periods of low

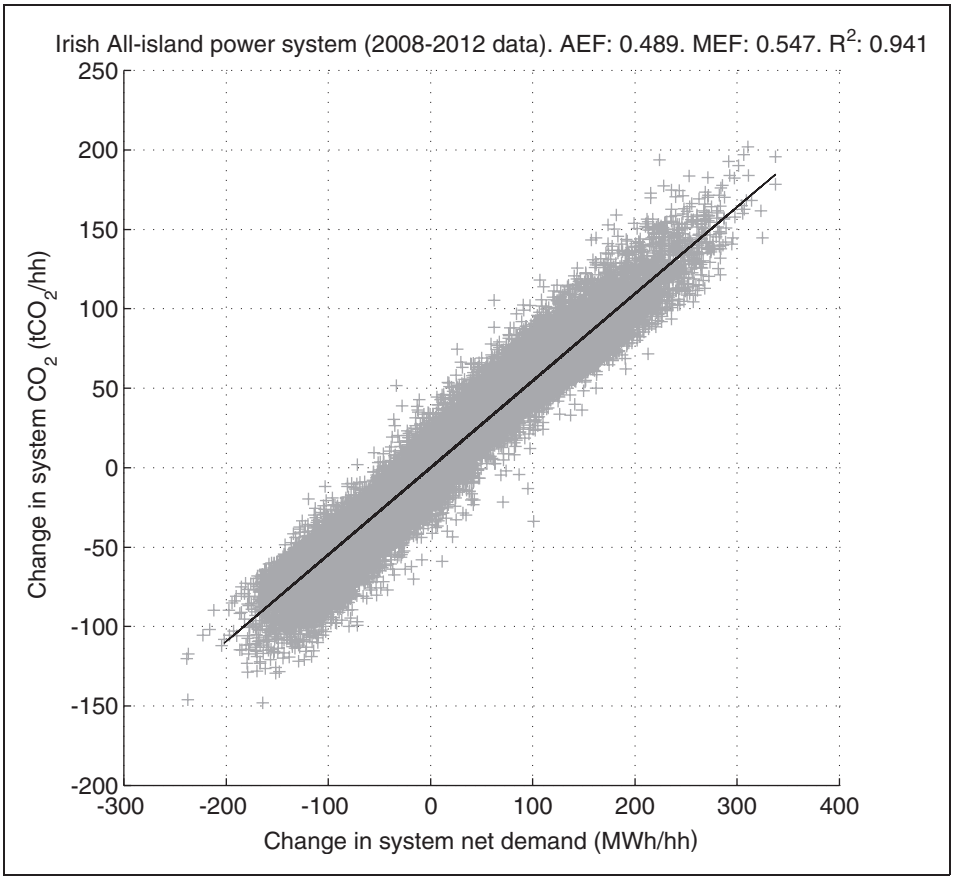

Figure 2. Average marginal emissions factor for the All-Island power system for the years 2008–2012. AEF: average emissions factor; MEF: marginal emissions factor.

demand, thereby smoothing out the net demand profile. While this is a common simplification of storage operation, it is possible to be more accurate about how storage might realistically be operated in the All-Island power system, by basing the third scenario on the operation of the actual pumped hydro systems already present in the power system. The actual operation of pumped hydro is illustrated in Figure 4, which shows the output over the period 2008–2012. Box plots are provided for each half-hour of the day. The central mark denotes the median, boxes extend to the 75th and 25th percentile, and whiskers extend to the most extreme points not considering the outliers, which are plotted individually. The data show that while the system is charged during the 'trough' and discharged during the 'peak', its operation is slightly more complex. In general, at night, the pumped hydro tends to be either off or charging at full power. Then during the day the pumped hydro tends to operate either at minimum generating power or at some higher output power following the variation in net demand, roughly matching the 'double hump' shape of the net demand profile. This results in the tall boxes in Figure 4.

The final four scenarios are based on storage that is operated specifically in relation to wind power output. The first of these (scenario 4) is based on a 'wind balancing' operating pattern, where storage is charged when wind output is high, and discharged when wind output is low, effectively turning wind power (plus storage) into baseload generation.[30–32] The remaining three scenarios consider the specific case where the storage is charged to reduce wind power curtailment. In this case, wind power acts as a marginal generator, reducing the charging marginal emissions factor. The extent to which it is reduced depends on a number of factors. The first is the system non-synchronous penetration limit (SNSP). This is an upper limit on the amount of demand that can be met by non-synchronous generation as a measure to ensure there is adequate inertia on the grid to safe-guard its stability. This is of particular relevance to the Irish power system due to existing levels of wind curtailment to not exceed the non-synchronous penetration limit,[43] and due to the expected considerable increase in curtailment in the future.[17]

As wind power is not considered synchronous generation, this means that charging the storage can only reduce wind curtailment by an amount proportional to the SNSP limit. The current limit is 50%,[43] which means that 50% of any increase in demand due to charging the storage has to be met by conventional synchronous generators. The next scenario considers a SNSP limit of 75%, which is reported to be

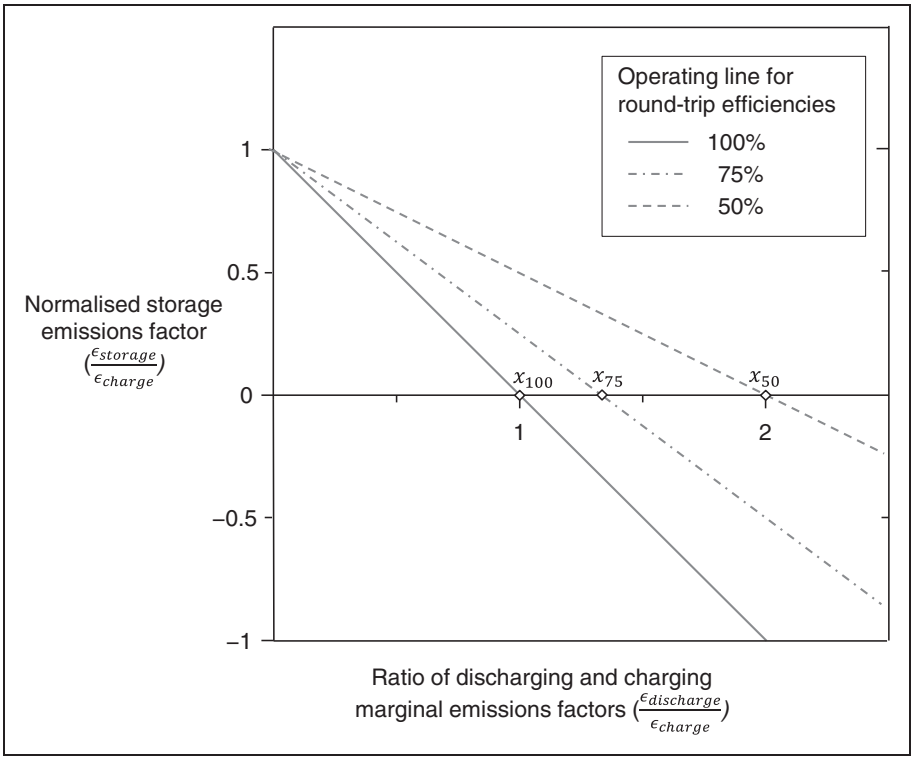

Figure 3. Graphical representation of the relationship between storage efficiency, discharging and charging emissions factors and resulting storage emissions factor. Points x_n indicate minimum ratios of discharging to charging emissions factors needed to achieve neutral storage emissions factors, where n is storage round-trip efficiency.

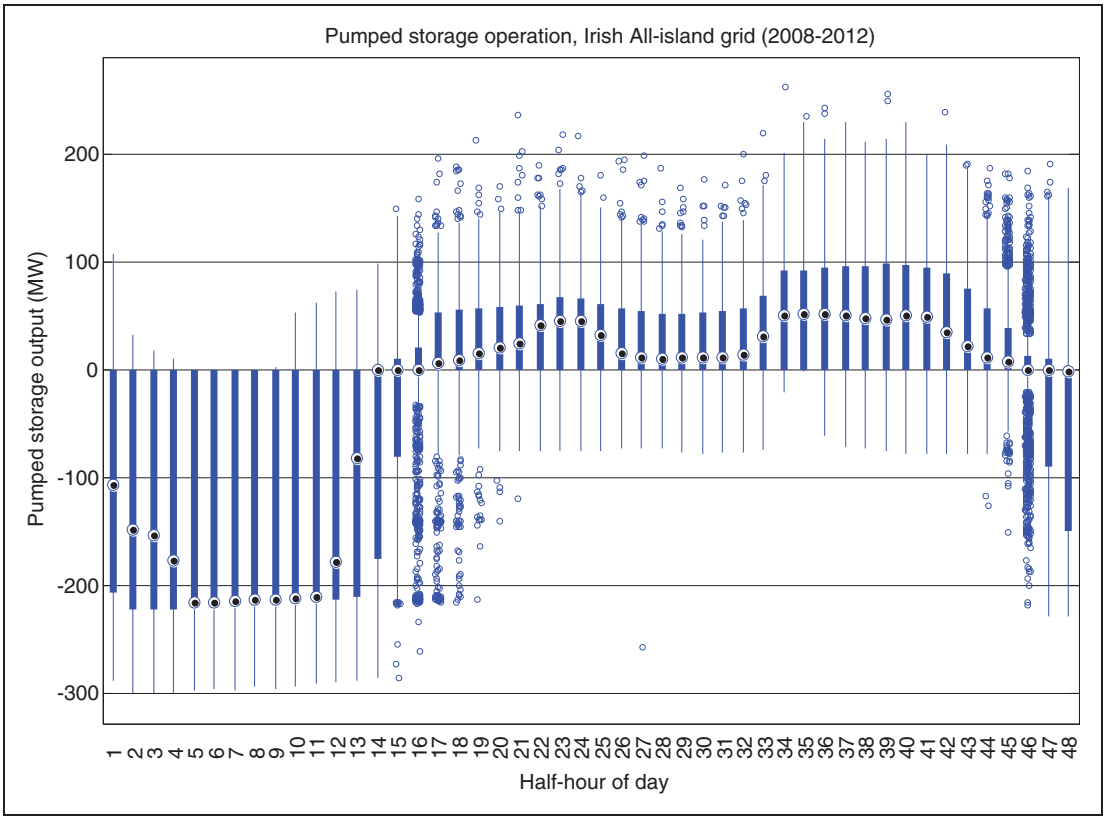

Figure 4. Power output of pumped hydro storage in the All-Island system (2008–2012) showing when the system is typically charging and discharging.

technically feasible by 2020.[44] The final scenario considers the case where there is no need to run synchronous generators in parallel with the storage, either because it is a synchronous machine itself, e.g. pumped hydro, or compressed air energy storage, or where the storage is 'generator integrated'[45] and where, from the grid's perspective, using the wind power to charge storage would appear the same as curtailing the wind farm's output.

Storage emissions factors are then calculated based on estimated charging and discharging marginal emissions factors using the data shown in Figure 2 but filtered according to the assumed storage operation in each scenario. How the data were filtered is described below and the resulting marginal emissions factors and storage emissions factors are shown in Table 4 for a range of storage efficiencies.

The first scenario (random operation) requires no filtering of the data and both the charging and discharging emissions factor are the same as the average (0.547 $kgCO_2/kWh$), which results in storage emissions factors that are positive, i.e. storage operated in this way increases emissions. The second scenario (peak shaving trough filling) requires us to estimate separate marginal emissions factors for discharging during peak times and charging during the trough. Figure 5 shows the relationship between the system net demand and the marginal emissions factor for the All-Island power system (dashed lines show the 95% confidence intervals). The figure shows a histogram of the net demand for the All-Island power system, and the corresponding marginal emissions factor for each 'bin' of net demand. This has been calculated in the same manner as described in Hawkes[34] by binning the marginal emissions factors according to system load, and performing a linear regression the same as shown in Figure 2 for each level of binned net demand. The marginal emissions factor can be seen to vary with the level of net demand – it is relatively flat for intermediate levels of demand, and rises for both low and high levels. This shows that plant with relatively high carbon intensity (e.g. peat, coal, oil, distillate) operates on the margin when net demand is high or low, while plant with relatively low carbon intensity (e.g. gas) operates on the margin for intermediate levels of net demand. We note that this is the opposite relationship to that of the GB system,[34] where coal operates on the margin for intermediate levels of net demand (as it was cheaper than gas at the time), while lower carbon generation (e.g. gas) operates on the margin for high and low levels of net demand.

Given these data, marginal emissions factors for charging and discharging were estimated for the 'peak shaving, trough filling' scenario by taking a weighted average of the marginal emissions factors in the bottom and top quartiles of net demand. The results are shown in Table 4 and indicate that

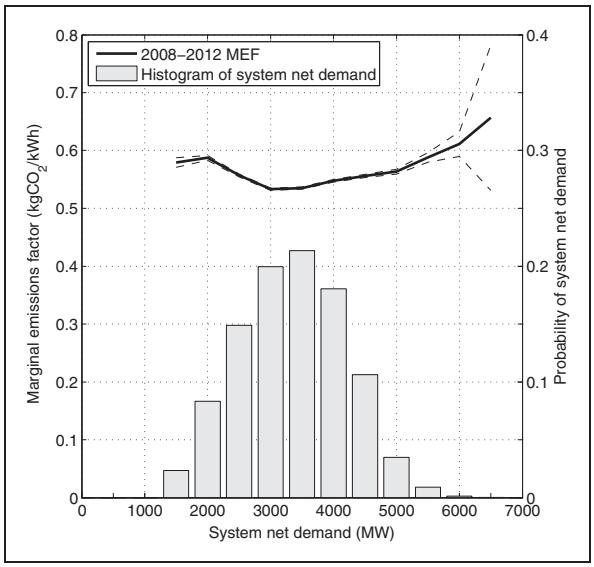

Figure 5. Histogram of system net demand (right axis) and marginal emissions factor (left axis).

Table 4. Estimated storage emissions factors for various storage efficiencies and assumed operation scenarios.

Scenario	1	2	3	4	5	6	7
Description	Random/uniform operation	Peak shaving, trough filling (weighted by upper and lower demand quartiles)	Realistic (based on actual pumped storage operation)	Wind balancing (weighted by upper and lower wind output quartiles)	Reducing wind curtailment (50% SNSP)	Reducing wind curtailment (75% SNSP)	Reducing wind curtailment (synchronous machine / wind-integrated)
Charging emissions factor (kgCO2/kWh)	0.55	0.57	0.54	0.56	0.28	0.14	0.00
Discharging emissions factor (kgCO2/kWh)	0.55	0.56	0.54	0.55	0.55	0.55	0.55
Cycle efficiency (%)	Storage emissions factor (kgCO2/kWh)						
100	0.00	0.01	-0.01	0.01	-0.27	-0.41	-0.55
90	0.05	0.07	0.05	0.07	-0.21	-0.35	-0.49
80	0.11	0.13	0.10	0.12	-0.16	-0.30	-0.44
70	0.16	0.18	0.16	0.18	-0.10	-0.24	-0.38
60	0.22	0.24	0.21	0.23	-0.05	-0.19	-0.33
50	0.27	0.29	0.27	0.29	0.01	-0.13	-0.27
40	0.33	0.35	0.32	0.34	0.06	-0.08	-0.22

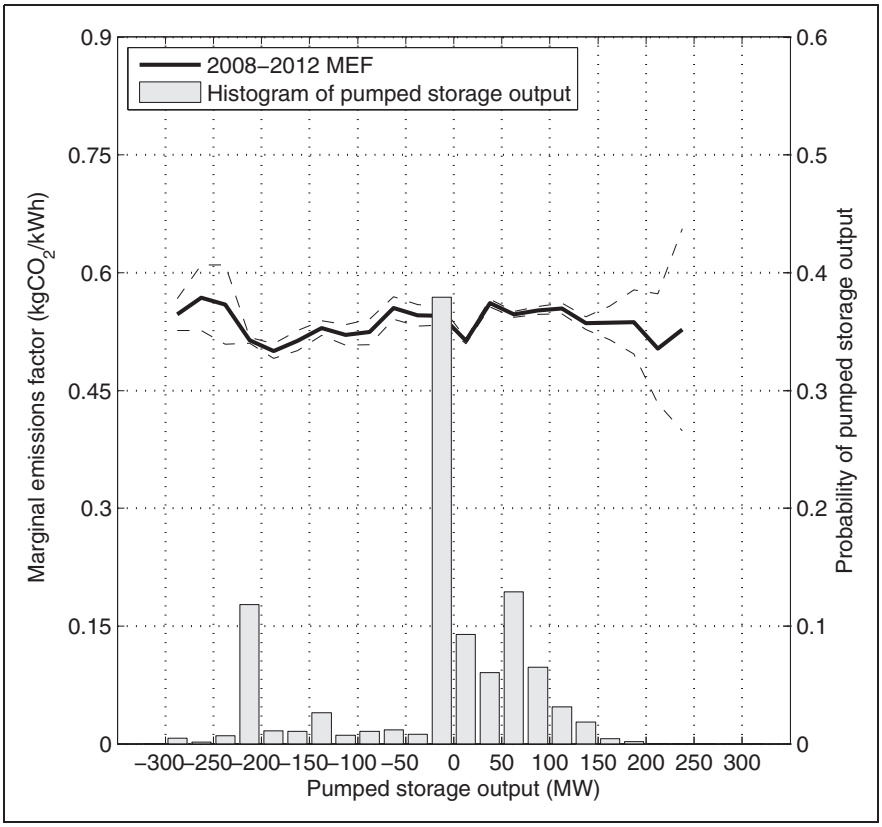

Figure 6. Histogram of pumped hydro output and binned marginal emissions factors for the All-Island power system (2008–2012).

the marginal emissions factors were nearly identical (0.569 $kgCO_2$/kWh for charging, and 0.555 $kgCO_2$/kWh for discharging) and that emissions are always increased under this operating scenario. We tested the sensitivity of this result to annual and seasonal fluctuations by performing additional calculations based on further binning of the data by year (see Appendix 1), and by month (not included). The results demonstrate that this finding is relatively robust to both seasonal and annual fluctuations in demand and generation. In all, 2008 appears to be the only year where storage with a not unreasonably high round-trip efficiency could be expected to have a positive in-use short-run environmental impact.

Marginal emissions factors for charging and discharging were estimated for the third scenario, 'realistic operation' based on actual pumped hydro operation, in the same way as for the previous one but this time based on a histogram of storage output and corresponding 'binned' marginal emissions factors as shown in Figure 4. Rather than basing the estimated marginal emissions factors for charging and discharging on the quartiles of the histogram distribution, they are instead based on the negative and positive portions of the distribution, respectively, weighted by pumped hydro electricity use and supply. The results are shown in Table 4 and indicate nearly identical marginal emissions factors for charging and discharging, which again results in increased emissions for realistic levels of storage round-trip efficiency.

Charging and discharging marginal emissions factors for the 'wind balancing' operation (scenario 4) were estimated based on the bottom and top quartiles of wind power output, and the corresponding binned marginal emissions factors, shown in Figure 7. Marginal emissions factors are flat for low and medium levels of wind output, but increase for very high levels of wind power. This could be due to the fact that in the Irish All-Island system wind power has been shown to displace generation with relatively low carbon intensity compared with the average,[36,37] which would result in higher carbon plant being left on the margin at high levels of wind output. The results (Table 4) are effectively the same as for previous scenarios and highlight that using storage to turn wind power into baseload results in increases in emissions.

The final three 'avoiding wind curtailment' scenarios assume the same discharge marginal emissions factor as the 'wind balancing' one, but have a reduced charging marginal emissions factor compared with the wind balancing scenario. The 50% SNSP scenario has a charging marginal emissions factor that is 50% of that of the 'wind balancing' scenario, the 75% SNSP scenario is one-quarter of it, while the final scenario has zero emissions associated with charging. As shown in Table 4, the results for these final three scenarios are positive for the efficiencies considered here, i.e. these result in decreases in emissions, with the exception of the 50% SNSP scenario for efficiencies below 50%.

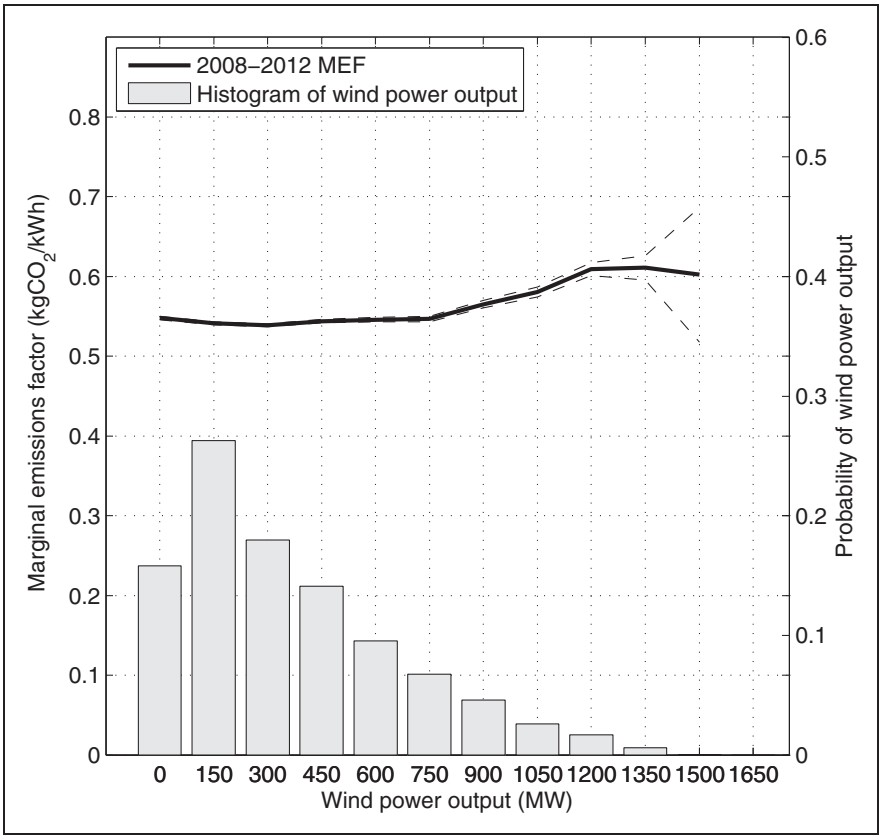

Figure 7. Histogram of wind output and corresponding binned marginal emissions factors for the All-Island power system (2008–2012).

Discussion

The results provide an estimate of the marginal impact of electricity storage in the Irish All-Island power system over the years 2008 to 2012, as well as the short-run marginal impact of storage in the (short-term) future. The results show that operating storage in a 'peak shaving trough filling' mode can actually increase overall carbon emissions in the All-Island power system. This is because the marginal emissions factors do not have a monotonically increasing relationship with net demand: as shown in Figure 5, the relationship is parabolic. Therefore, in the short-run, shifting demand from the peak to the trough of demand does not provide enough benefit to compensate for the round-trip losses of the storage. While the emissions factors are relatively low for high round-trip efficiency storage, we note that these results exclude any consideration of the cradle-to-gate environmental impact and should therefore be considered lower bounds of the overall short-run impact.

This finding may be transferable to other power systems in which the marginal emissions factor does not increase monotonically with net demand. For example, the GB grid also has a parabolic relationship for the years 2002–2009,[34] though inverted compared with the Irish power system, while for the majority, US regions marginal emissions factors decrease with net demand for the years 2006–2011.[35] Logically, therefore, the short-run marginal impact of storage in the GB and US power systems, for peak shaving and trough filling, will also be to increase carbon emissions.

When operated in a 'wind balancing' mode, the results also show that carbon emissions increase in the short-run in the Irish power system for all storage technologies. This is because there is little relationship between the marginal emissions factor and wind output, except at high levels of wind power, when the marginal emissions factor increases slightly. In the short-run, therefore shifting demand from periods of low wind output to periods of high wind output increases emissions and storage round-trip losses will only increase this further. These findings provide support to the argument that grid-connected intermittent renewables like wind power are the last to operate on the margin, and the last to be stored,[33] meaning that operating storage in wind-balancing mode may well increase emissions in the short-run. This argument also applies to storage operated in balancing mode with other forms of intermittent renewables – an argument which is particularly important to the growing interest in adding battery storage to domestic solar photovoltaic systems to increase self-consumption.[40,46]

By contrast, carbon emissions are reduced when storage is operated to reduce wind power curtailment,

as in this specific case, it is wind power that is operating on the margin. This is true for any large power system. For smaller power systems, such as the Irish one, which have a system non-synchronous generation penetration limit (SNSP), the results show that this finding is only applicable in three situations:

1. storage technologies that are non-synchronous (e.g. batteries) but have a round-trip efficiency high enough to compensate for their need to be run in parallel with an amount of thermal generation determined by the SNSP;
2. non-synchronous storage that is wind generator-integrated and so can be charged by the wind farm operator instead of 'dispatching down' their wind turbines;
3. synchronous storage (e.g. pumped hydro) that can provide system inertia and thereby form part of 'synchronous generation' even when charging.

We note that this result is based on the current definition of SNSP, which includes the implicit simplifying assumption that only synchronous generation can provide inertia. We note however that non-synchronous generation can be operated, with appropriate modifications, to provide 'synthetic inertia'.[47] It is therefore reasonable to assume that the SNSP concept might be modified in future to account for such advances, in which case this result would need to be re-evaluated. Nonetheless, these findings emphasise that, for power systems with high penetrations of non-synchronous generation from renewables, energy storage technologies that can provide system inertia are superior to those that cannot.

The results show that scenarios that are based on operating storage for economic gains can have a negative short-run environmental impact (increasing emissions). While the scenarios that are based on operating storage for environmental gains are, more than likely, economically unfavourable. This is because wind curtailment is still relatively rare, will increase gradually in-line with installed wind penetration, and will have volatile returns due to the natural variability of wind output. As a result, there is a risk of economics and the environment not working together in the short-run when it comes to adding storage in current power systems, a finding which echoes those of similar studies based on US power systems data.[39]

Our results are based on the simplifying assumption that storage is operated in a consistent pattern such that the allocation of average marginal emissions factors for charging and discharging is valid. Inspection of Figure 2 indicates that the instantaneous marginal emissions factor is variable, and future work could investigate whether operational patterns can be found within this that would reduce emissions. The relatively simple approach presented here could also be refined by developing generator-level emissions rates, which could also take into account the effect of part-loading on thermal efficiency, and the impact of various storage operating scenarios at the level of the individual generators. Future work could also extend the present study to include economic assessments of these scenarios.

All of the above, however, is based on a short-run impact assessment. The method, by definition therefore, assumes that the storage does not have a structural impact on the power system, e.g. in terms of changes in the merit-order, or commissioning and decommissioning of plant. This is appropriate for considering relatively small incremental changes in grid-connected electricity storage. The results are therefore particularly relevant to small-scale, distributed 'behind the meter' storage, which may have relatively short operational lifetimes, and which may have variable operating patterns, as well as marginal changes in the operation of existing storage systems such as pumped hydro. Future work could extend the method presented here to consider assumed changes to merit-order.

Furthermore, it is important to point out that while the environmental case may be negative in the short-run for some of the scenarios considered here, the long-run environmental case may well be different. First, electricity systems are decarbonising, which can be expected to make considerable changes to marginal emissions factors, meaning that caution should be taken when extrapolating short-run assessments into the future.[15] For example, there may well be considerably larger amounts of wind power being curtailed and therefore more opportunities for storage to reduce emissions. Second, storage can be expected to have a significant structural impact on the electricity system, for example by avoiding the commissioning of new peaking plant, increasing the capacity factor of installed generators, and allowing more low-carbon generation to be installed than would otherwise have been the case without it. Third, the present analysis is based on an electricity system and a merit order of generator dispatch that puts a very low price on carbon emissions. If a higher price were used, then the marginal emissions factors would be strongly correlated with net demand, and storage would therefore have an environmental benefit under any arbitrage scenario provided adequate round-trip efficiency. These effects are not factored into short-run impact assessments, but should be in long-run assessments. This is why both long-run and short-run impact assessments are important, and why both should be considered within the overall environmental impact assessment of storage.

Conclusions

Empirical data were obtained on the observed dispatch of each large generator in the Irish All-Island power system for the years 2008 through 2012 and used to estimate the system's marginal emissions factor

(0.547 $kgCO_2$/kWh). This value is substantially higher than the estimate of the average emissions factor for the same period (0.489 $kgCO_2$/kWh) highlighting the potential to underestimate the impact of demand-side interventions if the lower value is used incorrectly.

With the aim of estimating the short-run in-use environmental impact of electricity storage in the Irish All-Island power system, the marginal emissions data were filtered according to various storage operation scenarios to estimate marginal emissions factors for storage charging and discharging. These were combined with the storage round-trip efficiency to provide an estimate of the 'storage emissions factor' – the carbon emissions impact associated with each unit of energy delivered from storage.

When consistently operated in a 'peak shaving trough filling' mode, and when operated in a 'wind balancing' mode, the results show that carbon emissions increase in the short-run for all storage technologies. This is because the marginal emissions factors in the All-Island power system have neither an increasing relationship with net demand nor a decreasing relationship with wind power output. The former is also true for the GB and US power systems, with the logical conclusion that the short-run marginal impact of storage operated for peak shaving trough filling in the GB and US power systems would also be to increase carbon emissions.

By contrast, carbon emissions are reduced when storage is operated to reduce wind power curtailment, as in this specific case, it is wind power that is operating on the margin. For power systems such as the Irish one, which have a SNSP limit, the results show that energy storage technologies that can provide system inertia, such as pumped hydro or compressed air energy storage, provide considerably greater carbon reductions as they avoid the need to be run in parallel with synchronous fossil-fuel generators.

The results highlight a tension between economic gains and environmental gains; the scenarios in which storage is operated for economic gains increase emissions, whereas those that decrease emissions are unlikely to be economically favourable.

While some of the scenarios considered here indicate a negative environmental impact of storage, this is a short-run assessment only. Ultimately, in a fossil fuel-free world, energy storage will become essential to the secure operation of the grid, and the long-run environmental impact of storage has the potential to be positive. Both long-run and short-run impact assessments are important, and both should be considered within the overall environmental impact assessment of storage.

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Appendix 1

Table 5. Estimated storage emissions factors for the peak shaving trough filling scenario, showing the variation across the 5 years of data.

Description	Peak shaving, trough filling (weighted by upper and lower demand quartiles)				
Year	2008	2009	2010	2011	2012
Charging emissions factor (kgCO2/kWh)	0.48	0.47	0.52	0.58	0.66
Discharging emissions factor (kgCO2/kWh)	0.57	0.53	0.58	0.58	0.50
Round-trip efficiency (%)	Storage emissions factor (kgCO2/kWh)				
100	-0.09	-0.06	-0.06	-0.01	0.15
90	-0.03	0.00	0.00	0.05	0.20
80	0.02	0.05	0.05	0.11	0.25
70	0.08	0.10	0.11	0.17	0.30
60	0.14	0.15	0.17	0.23	0.35
50	0.20	0.21	0.23	0.29	0.41
40	0.25	0.26	0.28	0.34	0.46
Min. round-trip efficiency for neutral storage emissions factor	84%	89%	89%	99%	N/A