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PRO LOW CARBON: CARBON IMPACT OF DSO FLEXIBILITY SERVICES

A REPORT FOR WESTERN POWER DISTRIBUTION

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EXECUTIVE SUMMARY

Future Flex is an innovation project striving to increase the uptake of domestic solutions in the provision of DSO services. It is a joint project delivered by Western Power Distribution (WPD), Everoze and Smart Grid Consultancy (SGC), funded by the Network Innovation Allowance (NIA). Pro Low Carbon is a workstream within the Future Flex programme.

The objective of Pro Low Carbon is to explore and understand the carbon impact of procuring DSO services from local flexibility technologies.

METHODOLOGY

Assessing the carbon impact of DSO flexibility services requires a specialised approach. Measuring carbon impact is not the same task as measuring carbon emissions. An understanding of total greenhouse gas emissions is useful when dealing with energy generation, but the role of flexibility services is not simply to supply electricity to the grid. Flexibility services interact with the electricity network and influence the makeup of grid generation. The impact of this interaction needs to be measured, which is why measuring carbon emissions from just the flexibility asset itself is not sufficient. Understanding the impacts arising from both the flexibility technologies themselves and their interactions with the grid requires a unique approach.

To understand the impact of procurement decisions we must be able compare different technologies. Our methodology enables the impacts of different technology use cases to be viewed alongside each other. It measures impacts relative to a base case of not procuring the DSO service. This is known as a consequential approach.

The use of marginal carbon intensity data materially affects the results of this work. A common alternative in carbon accounting is to use average grid carbon emissions. The carbon impact hierarchy for the different technology use cases assessed in this work is highly sensitive to the assumptions and data sources used, including the type of grid carbon intensity data selected.

Our methodology adopts a holistic approach to carbon assessment. By calculating impacts from both operational and non-operational phases of a flexibility technology's life the full carbon impact of DSO service provision is captured. Carbon impact is defined as the sum of operational and non-operational impact, as depicted in Figure 1.

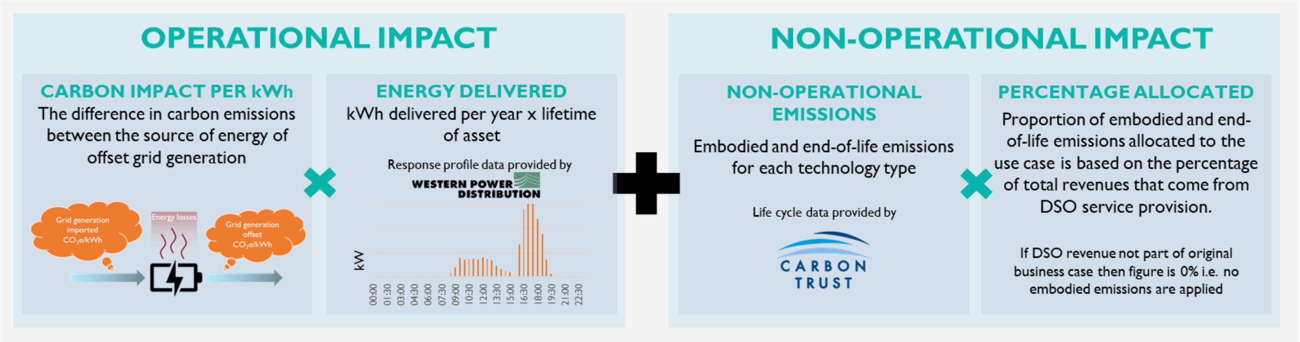

Figure 1: Pro Low Carbon's methodology for calculating carbon impact

Operational impact arises from the active provision of DSO services. This direct carbon impact is calculated for each technology use case. Operational impact reflects the difference in carbon emissions between two factors:

I. **Energy used to provide the DSO service**. For batteries and demand-side response, this energy is sourced from the electricity grid (with the carbon intensity of this source varying over time). For thermal generators, the energy source is fuel (natural gas or diesel).

II. **Offset grid electricity**. National level marginal grid carbon intensity data has been used in this work, provided by carbon data specialists Tomorrow.

Operational impacts are calculated as described in Figure 2. This calculation is built upon asset utilisation assumptions for DSO services, here representing the requirements of service delivery in one of WPD's Constraint Managed Zones.

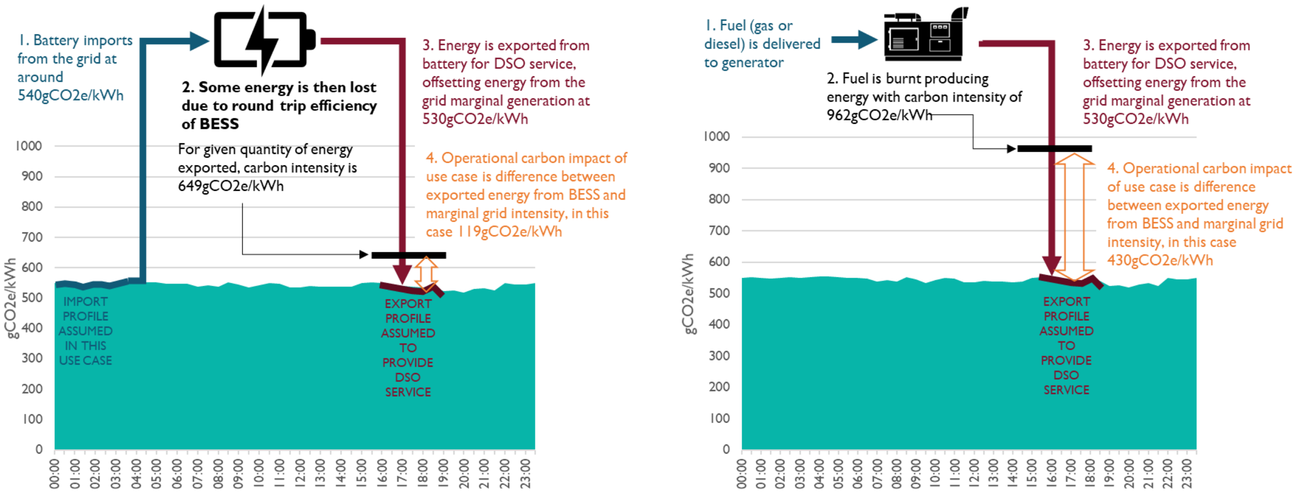

Figure 2: Calculating operational carbon impact for different flexibility technologies

Non-operational impacts are made up of embodied and end-of-life emissions. The Carbon Trust have provided data on non-operational emissions to this work, drawn from peer-reviewed life cycle assessments. The core methodological challenge was to establish the proportion of these emissions that should be assigned to the provision of DSO services. Only a proportion of non-operational emissions can be attributed to the carbon impact of DSO flexibility services because the technologies providing these services typically have multiple roles – including heating, mobility, and provision of ancillary services to National Grid ESO. The Pro Low Carbon methodology allocates a proportion of non-operational emissions equivalent to the contribution that DSO service revenues make to the asset investment case.

RESULTS

Key results are summarised in Figure 3.

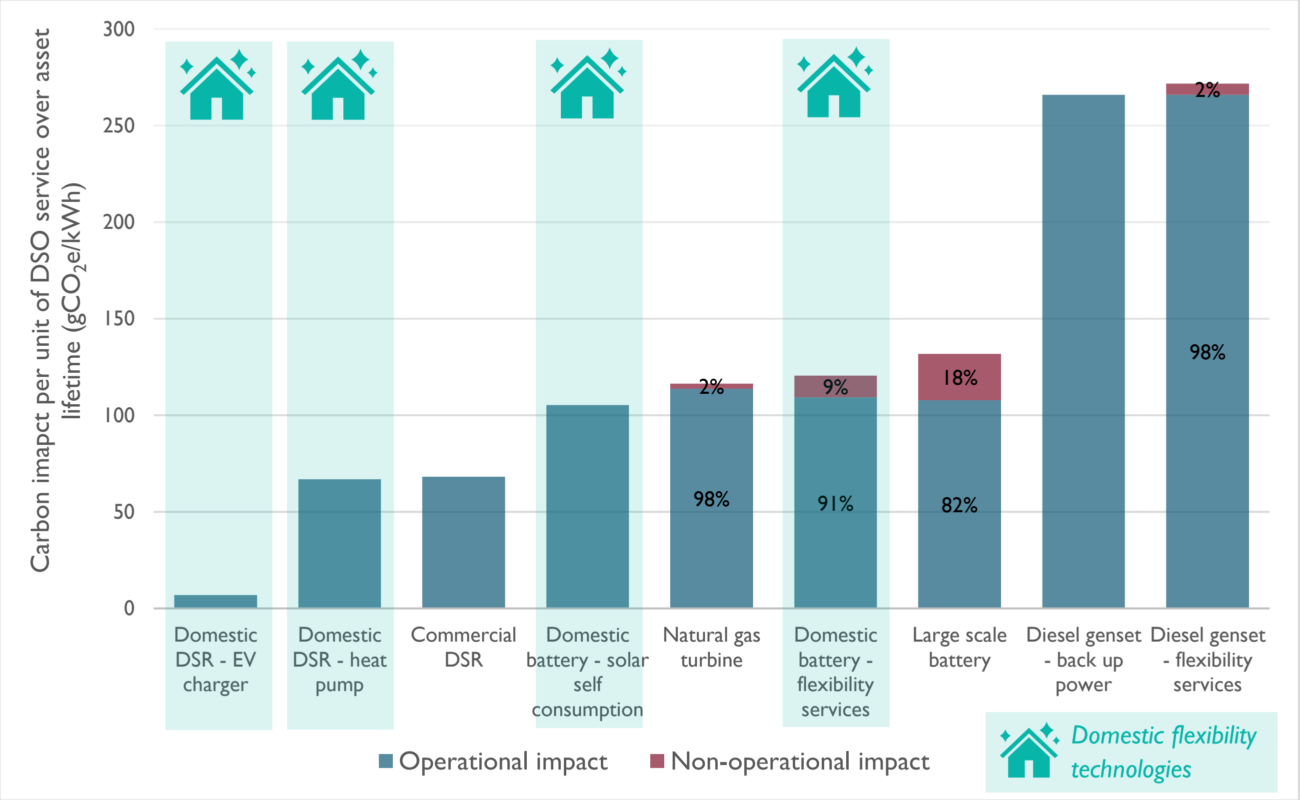

Figure 3: The carbon impact of DSO service provision by local flexibility technologies

DSO services have a carbon impact. The decision to procure a DSO service from any technology has an associated carbon impact and this impact varies with every technology and use case combination. The results show that this impact is between 7 and 272 grams of carbon dioxide equivalent per kWh of service provided, relative to a base case of not procuring the service. This study has not considered the carbon impact associated with alternative options to DSO services, such as investment in network infrastructure.

Operational emissions are the primary driver of carbon impact. The non-operational emissions allocated to the provision of DSO services are low, never exceeding one fifth of the total carbon impact. The low allocation of non-operational emissions directly reflects the low contribution of DSO services to an asset's total revenue stack.

▶ **Demand response (DSR) has the lowest impact of all technologies assessed at 7-68gCO2e/kWh.**

There are two primary reasons for this result:

- **Low or zero losses**: The losses associated with DSO service provision by DSR are low. Losses associated with DSR are also known as rebound losses, which describe the increase in total energy consumption that results from the demand response action.
- **Zero embodied emissions**: No embodied emissions are applied to DSR use cases because the assets either pre-exist or do not rely upon DSO services for their investment case.

Electric vehicle chargepoints are the leading low-carbon performer with an impact of just 7gCO_2e/kWh. This is because there are no rebound losses associated with shifting EV charging demand; the same quantity of energy is needed to charge the car regardless of the time of day that this consumption takes place. The carbon impact derives solely from the difference in the carbon intensity of marginal grid generation during the response period and the period to which demand is shifted.

▶ **Domestic flexibility solutions generally have a low carbon impact. Next in the hierarchy after EV chargepoints are heat pumps, then domestic batteries.**

The primary driver of the difference between these three technologies is the effect of losses. There are no rebound losses associated with EV chargepoints, whereas demand response provided by shifting heat pump use requires an increase in total energy consumption if the core function of the technology (heating the home) is to be maintained. Domestic batteries show the highest losses of the three as a consequence of the round-trip efficiency of battery storage technology.

▶ **Battery projects have a mid-level carbon impact of 105-132gCO_2e/kWh when using marginal grid carbon intensity data.**

At present there is minimal difference in the carbon intensity of the electricity imported and the grid generation that is offset. This means that the primary driver of operational emissions is the difference in the quantity of electricity imported and the quantity of electricity exported, as determined by the battery round trip efficiency.

Non-operational emissions on a per-MW basis are relatively high. This can be attributed to the energy intensive processes and raw materials required to produce battery cells. However, only a small proportion of the total non-operational emissions are allocated to the provision of DSO services. The order of results for total carbon impact is set by the different levels of allocated non-operational emissions within the different battery use cases.

▶ **Natural gas turbines have a mid-level carbon impact of 116gCO_2e/kWh, which is likely to increase over time.**

Operational emissions dominate the carbon impact of gas turbines because of their relatively high direct combustion emissions and the long lifetime of the technology. These operational stage carbon impacts are also likely to increase over time as the make-up of grid generation changes and the marginal grid carbon intensity falls.

▶ **Diesel gensets have the highest carbon impact of all technologies, at 266-272gCO2e/kWh.**

The high emissions associated with burning diesel fuel mean that operational emissions dominate the carbon impact, as they do for natural gas turbines. This carbon impact is likely to increase in the future as the carbon intensity of marginal grid generation falls.

FINDINGS

Assessing the carbon impact of flexibility services is challenging. This is due to the wide range of technologies providing DSO services, the variety of different use cases, challenges with the quality of available lifecycle assessment data, and the difficulty of appropriately allocating non-operational emissions.

The assessment of the carbon impact of landfill gas presents particular difficulties. Because it makes use of the polluting waste product of a separate industry, landfill gas generation is generally regarded as having very low carbon emissions. However, this result can only be reached if the scope of the assessment is extremely wide, taking account of the effects that would arise if the gas were not captured for generation use. Calculating the impact associated with DSO service provision adds another complexity by heightening the importance of the base case that the results are being measured against.

At present, there are only minor impacts associated with the difference in timing of import and export from the electricity grid. The results suggest that optimising the timing of import to periods of low marginal carbon intensity currently has a limited positive benefit. This conclusion can be traced back to the low daily variation in marginal grid carbon intensity in the national level data set used in this study.

Changes in marginal grid carbon intensity will benefit flexible technologies and disadvantage thermal generators. The different time scales over which this change can be experienced affect flexible technologies and thermal generators differently:

- **An increase in intra-day volatility could allow demand response and battery storage technologies to optimise their actions to reduce carbon impact.** An increase in the daily volatility of grid marginal carbon intensity could be expected in the future. Including future projections of grid carbon intensity in this study would change the results by likely increasing the differential between the carbon intensity of the imported generation and that of the offset generation for DSR and battery storage. This work does not take account of the opportunity that these technologies have to optimise their behaviour to reduce carbon. An increase in the volatility of grid marginal carbon intensity would provide an opportunity for these technologies to optimise their behaviour to reduce carbon impact.
- **A fall in average annual gird marginal carbon intensity would disadvantage thermal generators.** The carbon impact of thermal generators would increase if the average grid marginal carbon intensity falls. This is because the carbon intensity of their source of energy (the combusted fuel) remains the same while the carbon intensity of the grid generation that they are offsetting reduces.

NEXT STEPS

The conclusions of this work present novel findings with implications for the treatment of carbon in flexibility markets. There are several areas where the work of Pro Low Carbon could be developed and applied in the future:

- Develop the carbon assessment methodology to apply to all flexibility markets, including national services procured by National Grid ESO.
- Investigate how to use the methodology to report on carbon intensity in flexibility markets, providing radical transparency on carbon impact internally within WPD and externally to market participants.
- Explore how to measure and communicate real time signals that could help local flexibility market participants reduce their carbon impact.
- Monitor the historical and ongoing carbon impact of WPD Flexible Power services.
- Investigate what measures could be used to reduce the carbon impacts of flexibility service procurement.

Improving the Pro Low Carbon methodology could provide more accurate results and lead to a deeper understanding of the different factors that influence the carbon impact of DSO services. Potential areas for development include:

- Using local level grid carbon intensity data instead of national data.
- Modelling the impacts of assets adopting operational strategies that are optimised to reduce carbon, rather than solely to maximise financial returns.
- Developing the methodology to apply to an even wider range of technology types and use cases.

1. BACKGROUND

1.1 FUTURE FLEX

Future Flex is a participant-led trial of second-generation DSO services, deploying step change innovations for procurement, testing and delivery suitable for domestic scale assets. It is a joint project delivered by Western Power Distribution (WPD), Everoze and Smart Grid Consultancy (SGC), funded by the Network Innovation Allowance (NIA).

Pro Low Carbon is one of three separate workstreams within the Future Flex project.

1.2 PRO LOW CARBON

Pro Low Carbon is an exploration of the carbon impact of DSO services. It aims to provide clarity on the carbon emissions associated with the procurement of DSO services from local flexibility technologies and lead to a better understanding of the environmental impact of ancillary electricity services at a local level.

The objective of Pro Low Carbon is to explore and understand the carbon impact of procuring DSO services from local flexibility technologies.

Delivering this objective will achieve the following:

- Provide WPD with an understanding of the carbon impact of their flexibility service procurement decisions.
- Provide information on the scale of carbon impacts from different flexibility technologies to electricity system stakeholders, including other DSOs, National Grid ESO, Ofgem and BEIS.
- Formulate a method of carbon assessment applicable to DSO flexibility services and the wide range of different technologies that can provide them.

1.3 PROJECT STRUCTURE

This report is the second of two deliverables. It details the assessment methodology used to calculate carbon impact, presents the results of applying this methodology to 9 different use cases, comments on the results, and summarises the highest priority areas of future research.

The first deliverable published under Pro Low Carbon was the Carbon Assessment Methodologies report. It provides a summary and critique of the common methodologies deployed to assess carbon emissions across different sectors, from corporate carbon reporting to product life cycle assessments. The report concluded that an assessment methodology suitable for application to local flexibility services should be:

Based on an LCA framework

Capable of including enviornmental impacts from all stages of the technology life cycle, not just the use phase

Include all major greenhouse gas emissions that can be converted to CO_2e

Be applicable to the technologies currently providing DSO services and to those that will do in the future

Be flexible to accommodate different levels of detail in the assessment

Also noted were several key considerations on how to develop a methodology in line with the above stated goals that remained relatively simple and widely applicable, including:

- How to efficiently quantify carbon emissions with one method that can be applied to a wide range of different technologies;
- How to account, within one framework, for the emissions associated from operational behaviours that vary from demand reduction to burning fuels;
- How to best allocate non-embodied emissions for technologies that provide multiple services and for which DSO service provision is not the primary role.

The methodology developed and deployed in this work is described in the following section.

2. METHODOLOGY

The methodology for this study has been developed specifically to enable a comparative understanding of the carbon impacts of different technologies providing DSO services. It measures the impact that procuring the service from a certain technology has on the electricity system and does so with a wide scope that includes emissions from both the operational and non-operation stages of an asset's life.

It is summarised in the schematic below:

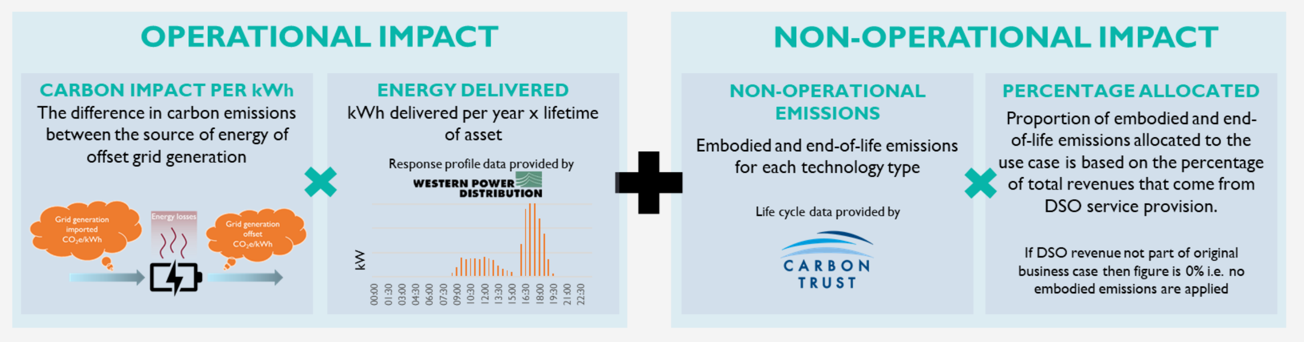

Figure 4: Pro Low Carbon's methodology for calculating carbon impact

Each section of the methodology is covered in detail, starting with the technology use cases used, followed by operational impact, non-operational impact, and the calculation model.

2.1 TECHNOLOGY USE CASES

A total of 9 different use cases have been assessed in Pro Low Carbon. The criteria for selecting these use cases aimed to ensure that the final selection:

- Included all the main technologies currently providing flexibility services to WPD;
- Was representative of the different use cases that such technologies are deployed in; and
- Also included key domestic technologies that do not currently provide Flexible Power services but that are expected to do so in the near future.

A summary of each use case is presented below. Full details, including the assumptions underpinning the modelling of each use case, are provided in Appendix B.

	TECHNOLOGY	PRIMARY USE CASE	ENERGY SOURCE
1a	Domestic battery	Increases self-consumption of rooftop solar and provides back up power	Rooftop solar generation during the day
1b		Managed by an energy flexibility aggregator to provide ancillary services to the ESO and DSO	Overnight import from the electricity grid
2	Large scale battery	Provides electricity market services including energy trading and ancillary services to the ESO and DSO	Evening import from the electricity grid
3	Demand response (commercial)	Non electricity market use (temperature-controlled storage)	Grid import (time-shifted)
4	Demand response (domestic heat pump)	Non electricity market use (domestic heating)	Grid import (time-shifted)
5	Demand response (EV charger)	Non electricity market use (EV charging)	Grid import (time-shifted)
6a	Diesel genset	Provides back up power to onsite energy consumer	Combustion of diesel fuel
6b		Provides electricity market services including energy trading and ancillary services to the ESO and DSO	Combustion of diesel fuel
7	Gas turbine (natural gas)	Provides electricity market services including energy trading and ancillary services to the ESO and DSO	Fuel combustion (natural gas)

The WPD DSO services modelled in this work can be provided by a relatively wide variety of technologies. This may not always be the case for other current DSO services or for services that emerge in the future. Stricter technical requirements could restrict the list of eligible technologies to just a subset of those included here.

2.2 OPERATIONAL IMPACT

Operational impact describes the carbon impact that arises from active provision of the DSO service. This section discusses the key areas that influence the calculation of operation impact, covering in turn:

- The emissions boundary
- DSO service response profile
- Energy import profiles
- Marginal grid carbon intensity
- Calculation methodology

2.2.1 Emissions boundary

Any approach to reporting or monitoring carbon emissions must consider where to set the boundaries of the assessment. In the energy industry, attempts to monitor carbon emissions have typically been restricted to the direct emissions from combustion of fuel. This approach makes sense for thermal generators that provide baseload power. However, it does not apply as well to assets providing ancillary services and to technologies such as renewable generation, energy storage and demand side response.

Energy flexibility services and the plethora of different technologies that provide them require a new approach for several reasons:

- **Non-combustion technologies are common:** Energy storage, demand side response and even renewable generation are now prevalent in energy flexibility markets. To understand the carbon impact of these technology groups it is necessary to take a more sophisticated approach than simply assuming zero carbon emissions.
- **Flexibility service provision impacts total grid generation:** Flexibility services are ancillary to the business of energy supply. They are designed to ensure that the electricity system runs smoothly and safely, rather than purely to deliver power onto the grid to be used by energy consumers. But the provision of such services still affects the balance of supply and demand. Other sources of generation on the grid will respond to these changes to ensure balance is maintained. This impact needs to be accounted for.
- **Asset utilisation is often low:** Carbon emissions of assets that export electricity to the grid for consumption are generally presented in terms of carbon emitted per unit of energy generated. Flexibility services, on the other hand, do not always require assets to provide power to the grid. Utilisation is often low, and renumeration made not per unit of energy but based on availability. These factors need to be considered.
- **Non-operational emissions cannot always be assumed to be negligible:** Because of the low utilisation of DSO services and the fact that many flexible technologies do not directly emit greenhouse gases, operational emissions can be relatively low. This means non-operational emissions cannot always be treated as negligible. For this reason it is necessary to account for emissions associated with material extraction, manufacturing and recycling/disposal in the assessment of carbon impacts of flexibility services.

The methodology used in this work aims to set the boundary of emissions consistently across different technology types and uses cases. It is not a completely comprehensive assessment and does not include all possible impacts that could be attributed to the provision of flexibility services. Instead it aims to include the most significant impacts and the majority of impacts which differ between technology use cases.

The sources of emissions that are included in the scope of this assessment are:

- Non-operational emissions of the flexibility assets, including both embodied and end-of-life impacts.
- Direct combustion emissions of grid generation, for technologies that source their energy from imported grid electricity.
- Direct combustion emissions from flexibility assets, for technologies that source their energy from combusted fuel.
- The emissions of grid electricity offset by the provision of the DSO service. This is made up of the combustion emissions of marginal grid generation.

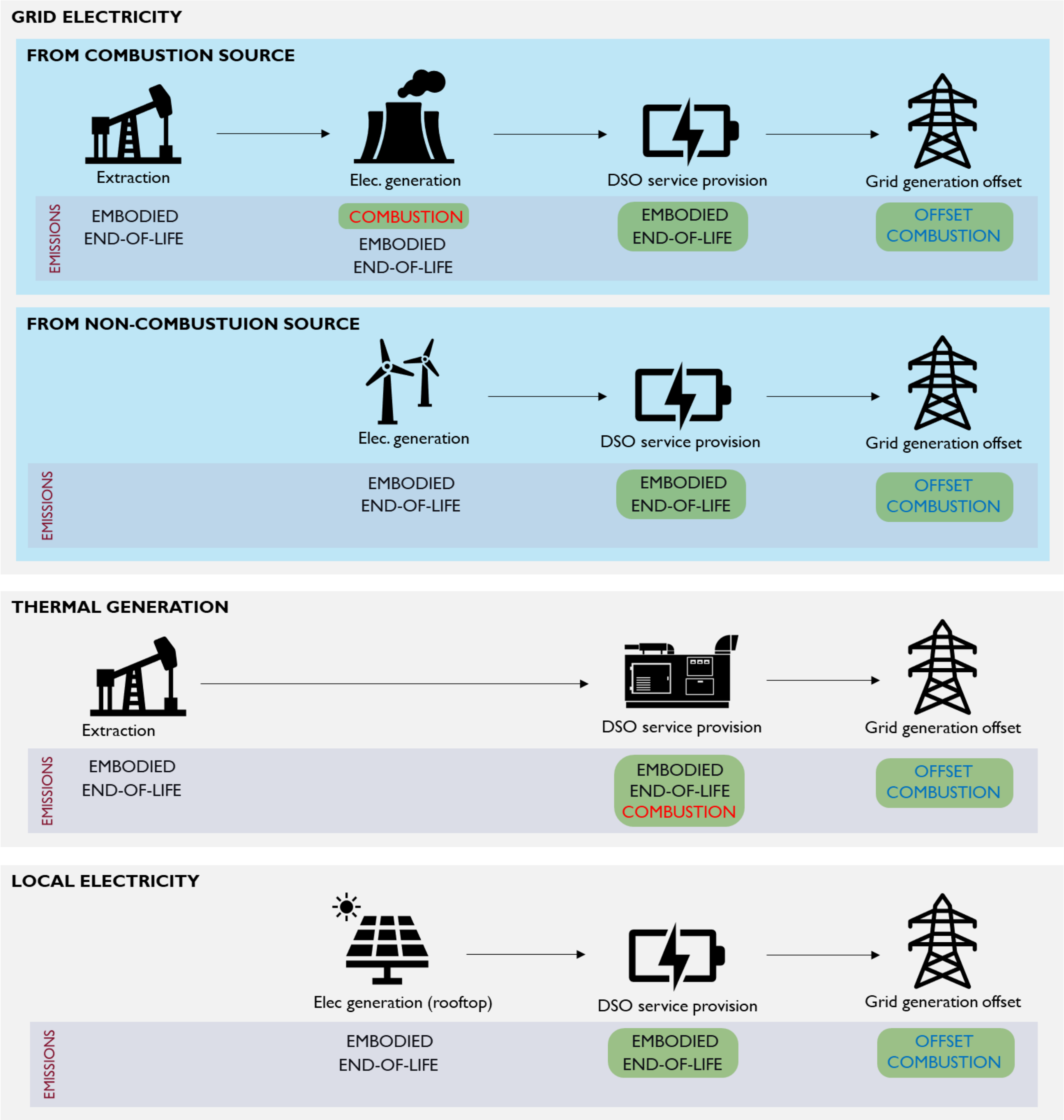

Figure 5: The emissions included in the scope of this assessment for different technology use cases. Included emissions are highlighted in green

2.2.2 Response profile

Pro Low Carbon is concerned with the carbon impact of DSO services. To understand how the provision of these services gives rise to carbon emissions, it is necessary to understand exactly what response is required from each contracted asset to deliver the service.

WPD procure flexibility services in certain areas of their network where physical infrastructure is under stress, known as Constraint Managed Zones (CMZs). These services provide either an increase in generation or a reduction in demand to relieve stress on the local network.

The requirements of each CMZ are different, reflecting the different patterns of local generation and demand and the varying nature of physical constraints each zone experiences. There is no standard service requirement. However, there are groups of CMZ where similarities can be drawn.

For this work a single CMZ has been chosen for all modelling scenarios. It has been selected to represent as close to a typical service requirement as is possible, defined by comparison of two parameters against the average for all CMZs:

- **Availability profile:** The maximum active power response capacity required across each half hourly period, measured in MW.
- **Annual utilisation:** The total energy delivered to provide the service over a year, measured in MWhs.

The availability profile and annual utilisation figures for this CMZ have been used to create a half hourly response profile covering a single year. This assumes that WPD procure exactly their target capacity over the year. This profile has several notable features.

- **It is seasonal:** The service is only required over four months of the year, from November through to February. This is consistent with the highest demand periods on the distribution network.
- **Demand is peaky:** The service is only required during the times of day when the network is under stress. For the CMZ in question this is primarily during the evening peak demand period, but also during the morning and early afternoon in some months.
- **Asset utilisation is low:** Even during the months where the service is required, the total demand on each contracted asset is low. This is in part due to the inconsistent nature of network constraints; only under certain relatively rare system condition will all contracted assets be required to respond with their full capability.

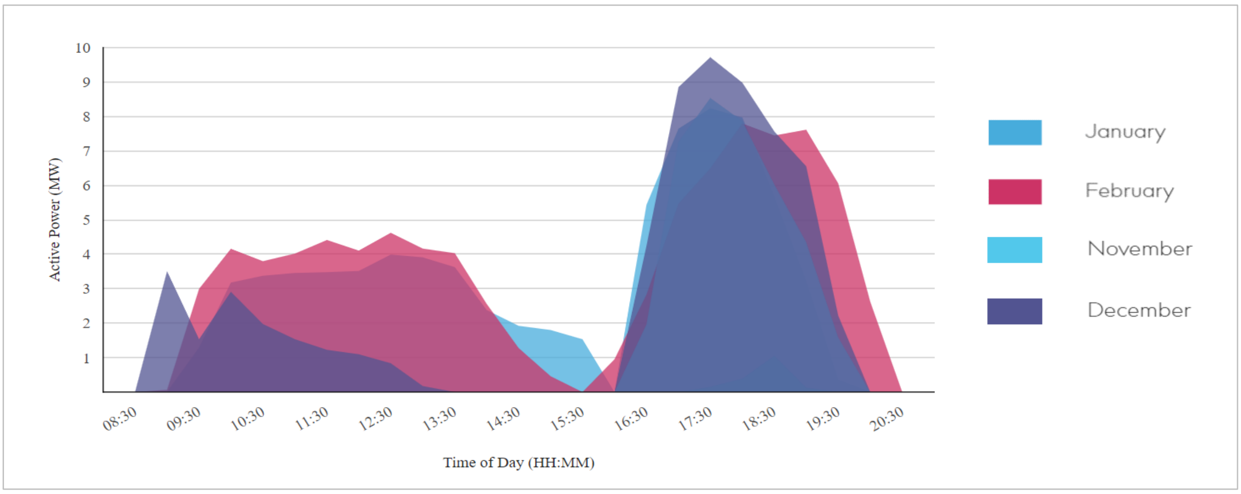

Figure 6: WPD Flexible Power service delivery windows for the selected CMZ

2.2.3 Import profiles

The response profile defines how the asset must operate to provide the DSO service to WPD, be it through export to the grid or reduction in demand. The other side of the equation is how and where the asset sources the energy it needs to provide this response, which is equally if not more important to the assessment of carbon impact,

This energy source varies widely across the different technologies and use cases. It can be categorised into three distinct groups as shown below:

Grid importing technologies are those that import electricity from the grid in order to provide the DSO service. They include all demand response use cases along with the large-scale battery use case. The carbon emissions associated with the imported energy of each use case are determined by:

- Timing of import
- Losses (efficiency losses or demand response rebound effect)

	Import timing	Losses/rebound
Demand response (C&I)	20:00 – 00:00	10%
Demand response (heat pump)	06:30 – 08:30 20:00 – 22:00	10%
Demand response (EV charger)	20:00 – 04:00	0%
Domestic battery	00:00 – 04:00	16%
Large scale battery	20:00 – 21:00	16%

Thermal generators are those that produce the energy required to provide the service on site through fuel combustion. In this work they include the diesel generator and gas turbine use cases. Two key parameters determine the carbon emissions associated with the source of energy:

- Fuel type
- Generator efficiency

	Fuel type	Gen. efficiency
Diesel genset	Diesel	30%
Gas turbine	Natural gas	28%

Local electricity consumers are a special case. They can be classed as non-generation technologies that source their energy from separate, on-site renewable generation. Here this group consists solely of the domestic battery self-consumption use case. The two key parameters are:

- Energy source
- Losses

	Energy source	Losses
Domestic battery	Solar	16%

2.2.4 Marginal grid carbon intensity

When providing DSO services flexibility technologies influence the balance of supply and demand on the grid. All technologies export or reduce their demand to deliver the service. A subset of these also source the electricity needed to enable them to provide the service by importing from the grid. Although the quantity of import or export from a single asset may be small, every kWh contributes to the balance of supply and demand on the network. An increase in demand must be met by an increase in generation, and equally an increase in export must be balanced by a reduction in generation from another point of supply on the grid.

Each kWh of electricity that is generated has an associated carbon intensity figure. So when DSO service provision results in a change in grid generation, then the carbon emissions of the grid are affected. To understand exactly what this effect is it is necessary to understand how the grid responds to changes in demand, and then to calculate the carbon intensity associated with this change.

This approach is consistent with the consequential methodology adopted in Pro Low Carbon. It enables fair comparisons to be made between different technologies, and provides the results needed to understand the carbon impact resulting from the procurement of DSO services.

▶ How grid generation responds to changes in demand

Grid electricity is provided by many different types of generation. Each generation technology has its own characteristics defining how it operates and how it adjusts its output in response to grid conditions. A large part of this generation acts as baseload generation and does not respond to changes in demand. So when a shift in demand triggers in a change in the total generation on the grid, it is not realistic to assume that this change is shared across all operational generators equally. The change will generally occur in one plant – the marginal generator.

▶ Identifying the marginal generator

Imagine a simplified grid where all generation is provided by either wind or gas. What happens when there is a change in demand? All other things being equal, the gas plant will change its output while wind generation remains constant. The simplest explanation for why this happens is because it costs more for the energy to be provided by the gas plant.

The marginal generator is the generator with the highest cost of generation at the time. This concept can be described by the marginal cost of generation, measured in £/MWh. The marginal cost of generation is how much it costs a plant to generate an additional MWh of electricity at any one point in time. It can also be thought of as how much money a plant would save by reducing its output by one MWh.

Different types of generating plant have different marginal costs of generation. Solar and wind generation have almost no costs associated with generating additional energy as their 'fuel' is available for free. The marginal cost of generation of a coal plant will be higher as it includes the cost of the coal that must be burnt to produce the extra energy.

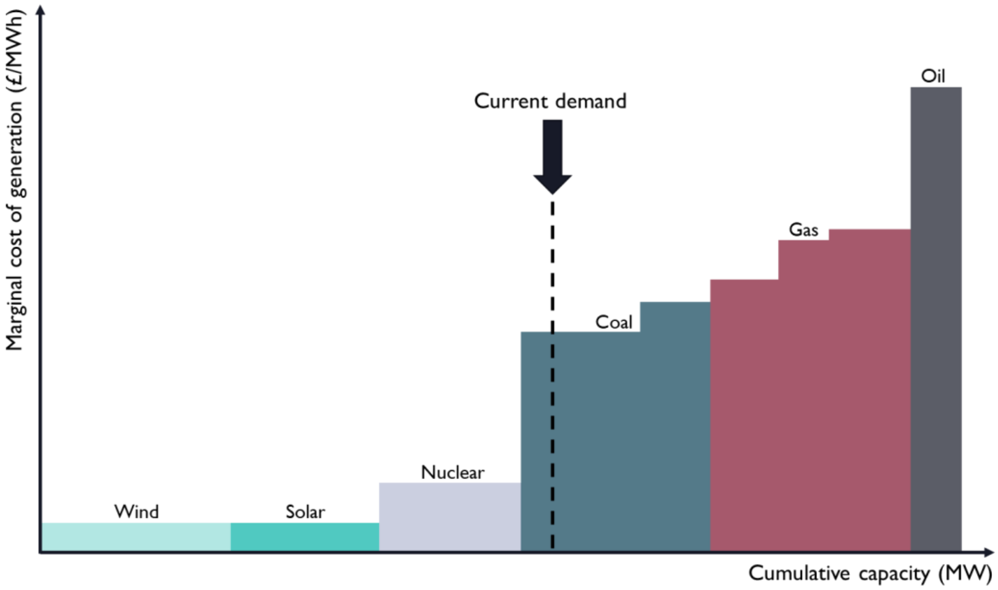

Figure 7: An example marginal cost curve of grid genertion

Figure 7 illustrates how generating plants can be stacked up in order of increasing marginal cost. This is how an ideal power system dispatches generation plant to keep the price of electricity as low as possible. Demand is first met by the generation with the lowest marginal cost, with successively more expensive generators dispatched until demand is met.

When demand changes, it is met by a change in the output of the generator with the lowest marginal cost that has spare capacity. In the scenario above, the marginal generator is a coal plant.

▶ Determining marginal carbon intensity

The marginal carbon intensity at a point in time is the carbon intensity of the marginal generator at that time. Expressed in units of gCO_2e/kWh it gives the mass of greenhouse gas emissions (measured in units of carbon dioxide equivalent) that are associated with each kWh of additional generation.

Marginal grid carbon intensity will change as the marginal cost curve and level of demand shift. So to account for how DSO services impact grid carbon emissions over time a timeseries of grid marginal carbon intensity is needed. Everoze has obtained this data from Danish carbon data specialists Tomorrow.

Tomorrow's methodology for calculating marginal grid carbon intensity uses a machine learning approach to determine the origin of marginal electricity, taking account of interconnectivity with other networks, weather conditions and more. More details are shown below.

Tomorrow: Marginal grid carbon intensity methodology[1]

1. Determine which national grid network will supply additional demand.

This calculation is particularly relevant to highly interconnected continental European grids, where additional demand is often met by import from other countries. Its impact on GB marginal grid carbon intensity is small but not negligible.

2. Find the generator technology that is marginal in each network

For each hourly period, each different generator type is considered separately. Changes in the output of each generating technology are treated as the sum of two components, one that is independent of changes in total grid generation (for example wind speed if considering wind generation) and one that depends on changes in grid generation levels (the marginal factor).

Tomorrow then apply machine learning techniques to datasets detailing past system conditions to determine the marginal and non-marginal components of changes in generation. They rely on more than 1000 different variables describing each situation, including consideration of weather and market conditions at the time.

3. Calculate marginal emissions

Once the marginal generation mix is known the carbon emissions of marginal generation is calculated using IPCC emissions factors[2] for each technology type.

This dataset shows little variation in GB marginal grid carbon intensity on both a daily and annual basis. It is largely dominated by gas generation.

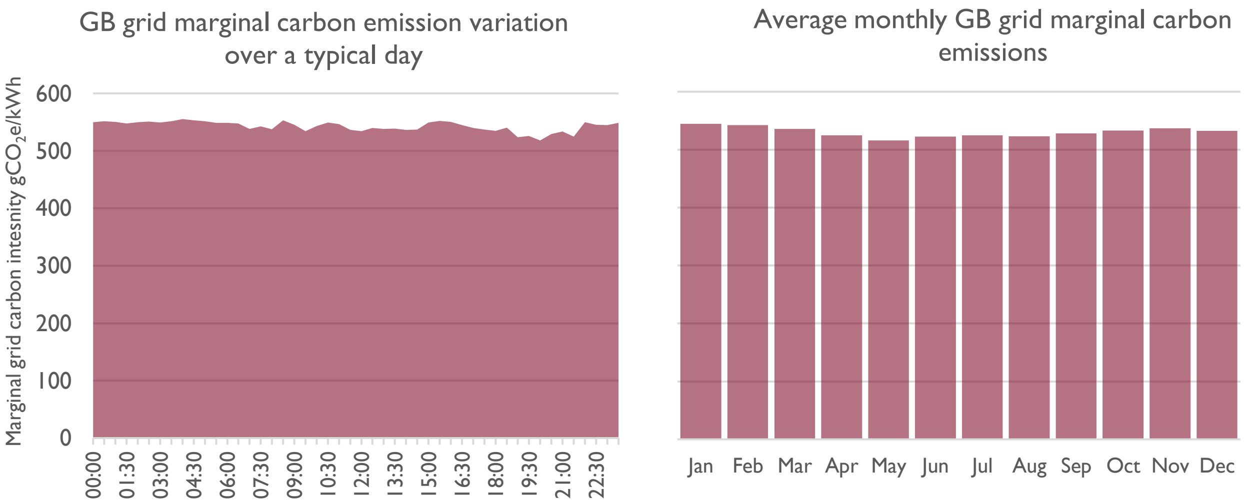

Figure 8: A summary of the GB grid marginal carbon intensity data used in this work

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[1] More information is available at tmrow.com/blog/marginal-carbon-intensity-of-electricity-with-machine-learning

[2] Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Annex III: Technology-specific cost and performance parameters

2.2.5 Calculating operational impact

The operational impact of providing a DSO service are defined by the difference between the carbon emissions incurred by the flexibility technology in providing the service and carbon emissions of the generation that is offset. The operational carbon impact of providing a DSO service can be determined by calculating this difference for each technology use case.

ENERGY GENERATED OR IMPORTED				**ENERGY OFFSET**		
Energy in	x	Carbon intensity	–	Energy offset	x	Carbon intensity
kWh		gCO2e / kWh		kWh		gCO2e / kWh

This calculation is repeated for each half-hour period over a year. The sum of the result for each half hour gives the operational carbon impact for the year. Multiplying this number by the lifetime of the asset gives the operational impact of providing the DSO service over the full operational period.

2.3 NON-OPERATIONAL IMPACT

Non-operational impacts are the carbon impacts associated with material extraction, manufacturing, transportation and ultimately disposal of an asset. They can be broadly categorised into the embodied emissions (the carbon emissions associated with the pre-operational stage) and the end of life emissions (those associated with disposal or recycling when the asset has reached the end of its useable life).

2.3.1 Inclusion of non-operational impact

Pro Low Carbon is concerned with exploring and understanding the carbon impacts of DSO service provision from flexibility services. This work does not aim to understand the impacts of all possible roles that a flexibility technology might play during its lifetime. It is interested only in the contributions that arise from the provision of the DSO service. This includes both the emissions that arise from actively providing the service (the operational impact) as well as embodied and end-of-life carbon emissions, where these can be attributed to the provision of the flexibility service.

The root cause of non-operational emissions can be traced back to the decision to invest in a technology. If this decision is not motivated by the opportunity to provide services to the DSO, then the procurement of flexible power services from this asset does not affect non-operational carbon emissions. In other words, DSO services are not a primary use of the technology; the investment would have taken place even if these services did not exist. In this scenario embodied and end-of-life carbon emissions should not be attributed to the carbon impact of DSO service procurement.

The alternate situation is when an asset is developed or invested in specifically with the intention of providing energy flexibility services. Here the availability of DSO services would be a contributing factor in the decision to invest; provision of DSO services is one of the primary uses of the technology. Thus the non-embodied emissions can, at least in part, be attributed to DSO service procurement.

The range of use cases can be split into two groups:

- Those where the investment decision was made with the intension of providing energy flexibility services. For these use cases, non-operational emissions are included.
- Those where the investment decision was not motivated by the opportunity to provide energy flexibility services. For these use cases non-operational emissions are excluded.

	TECHNOLOGY	PRIMARY USE CASE	NON-OPERATIONAL EMISSIONS
1a	Domestic battery	Increases self-consumption of rooftop solar and provides back up power	Excluded
1b		Managed by an energy flexibility aggregator to provide ancillary services to the ESO and DSO	Included
2	Large scale battery	Provides electricity market services including energy trading and ancillary services to the ESO and DSO	Included
3	Demand response (commercial)	Non electricity market use (temperature-controlled storage)	Excluded
4	Demand response (domestic heat pump)	Non electricity market use (domestic heating)	Excluded
5	Demand response (EV charger)	Non electricity market use (EV charging)	Excluded
6a	Diesel genset	Provides back up power to onsite energy consumer	Excluded
6b		Provides electricity market services including energy trading and ancillary services to the ESO and DSO	Included
7	Gas turbine (natural gas)	Provides electricity market services including energy trading and ancillary services to the ESO and DSO	Included

2.3.2 Allocation of non-operational emissions

Even for use cases where DSO services motivated the decision to invest, it will not be the case that these services alone were enough to trigger the decision that brought about the embodied and, ultimately, end of life emissions. For these technologies DSO services provide only part of the total revenue. Other services and opportunities would have also motivated the decision to invest.

Therefore it is not appropriate to allocate all non-embodied emissions to DSO service provision. Only a certain proportion will be allocated. The following method for calculating this allocation is based on asset finance principles and has been chosen on the basis of pragmatism, accuracy and fairness:

1. For each use case, calculate the returns required for an 10% internal rate of return (with a working average cost of capital of 8%)
2. Estimate what percentage of this return could be achieved by providing FP services[3]
3. Apply this same % to the total non-operational carbon emissions of the use case.

2.3.3 LCA data

Non-operational emissions data has been gathered from LCA studies. Everoze has worked with the Carbon Trust, established experts in the field of life cycle assessment, to source appropriate data covering each use case where non-operational carbon emissions are included.

TECHNOLOGY	EMBODIED EMISSIONS		END-OF-LIFE EMISSIONS	
	Data source	Year	Data source	Year
Domestic battery	Ecoinvent 3.6	2019	Ecoinvent 3.6	2019
Large scale battery	Baumann et al, Energy Technology	2017	Ecoinvent 3.6	2019
Diesel genset	Ecoinvent 3.6	2019	Ecoinvent 3.6	2019
Gas turbine	Ecoinvent 3.6	2019	Ecoinvent 3.6	2019

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[3] DSO service revenues are set at £6,000 per MW per year.

2.4 MODEL

Operational and non-operational carbon impacts are calculated in a model developed by Everoze. This model is designed to take the unique inputs of each technology use case and calculate the carbon impacts of each stage of the asset life. It is made up of three separate modules:

1. OPERATIONAL EMISSIONS	2. NON-OP. EMISSIONS	3. RESULTS
Inputs	**Inputs**	**Inputs**
DSO service response profile	Asset CapEx	Outputs of op. emissions module
Import / generation profile	Asset OpEx	Outputs of non-op. emissions module
Carbon intensity of import profile	Asset lifetime	Asset lifetime
Marginal grid carbon intensity profile	Target return (IRR)	Total DSO services provided (MWh)
	Asset operational lifetime	Cost of capital (WACC)
	DSO service revenue	
	Embodied emissions	
	End-of-life emissions	
Outputs	**Outputs**	**Outputs**
Carbon impact profile	Required non-DSO revenue	Total annual emissions
Total operational carbon emissions	Total revenue	Total lifetime emissions
	DSO service % of total revenue	Lifetime emissions per kWh service
	Total non-operational carbon emissions	

3. RESULTS

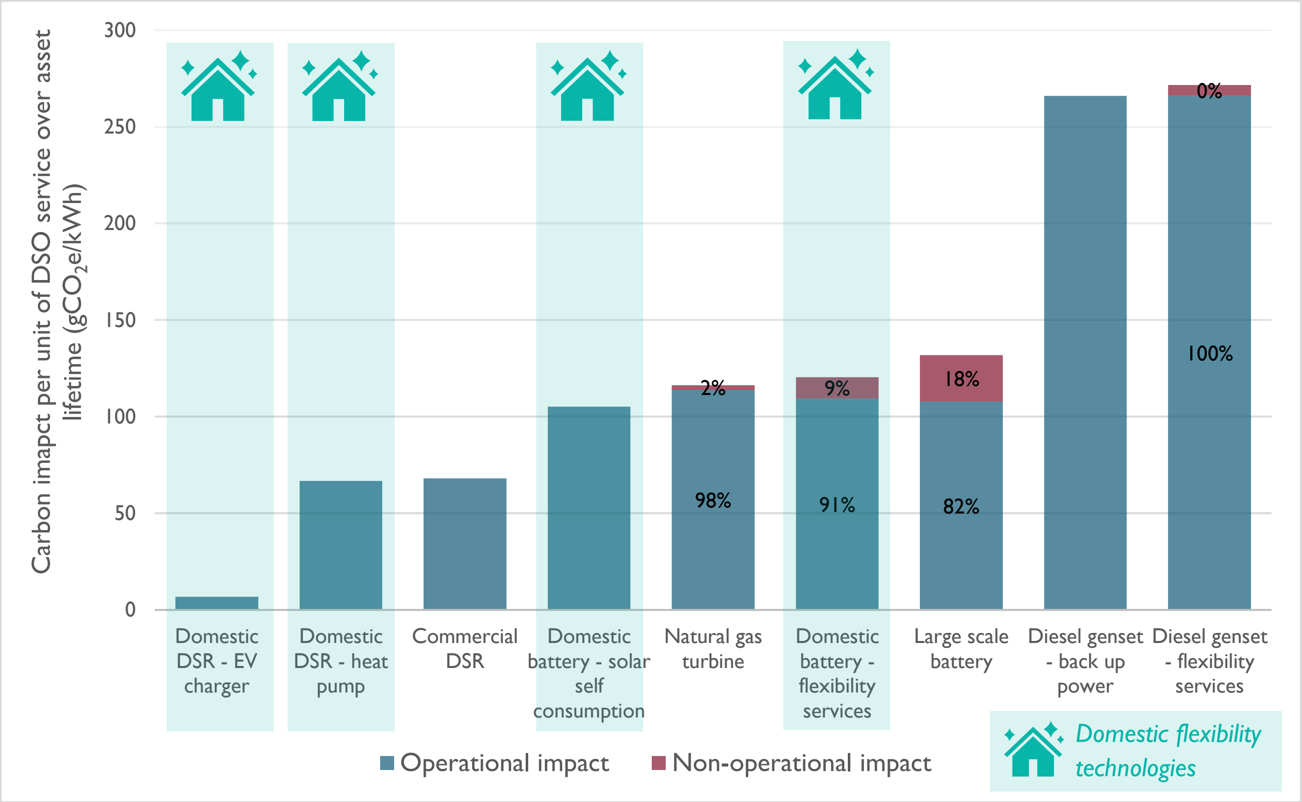

Figure 9: The carbon impact of DSO service provision by local flexibility technologies

Technology use case	Operational lifetime emissions	Non-op. allocated lifetime emissions	Total lifetime emissions	Total annual emissions	Volume of DSO service provided	Lifetime operational emissions per kWh DSO service	Lifetime non-operational emissions per kWh DSO service	Lifetime emissions per kWh DSO service
	[kgCO2e]	[kgCO2e]	[kgCO2e]	[kgCO2e]	[kWh]	[gCO2e/kWh]	[gCO2e/kWh]	[gCO2e/kWh]
Domestic DSR – EV charger	12	-	12	1	1,769	6.86	-	**6.86**
Domestic DSR – heat pump	16,872	-	16,872	1,687	252,659	66.78	-	**66.78**
Commercial DSR	17,209	-	17,209	1,721	252,659	68.11	-	**68.11**
Domestic battery – self consumption	133	-	133	13	1,263	105.20	-	**105.20**
Natural gas turbine	718,704	15,901	734,605	29,384	6,316,485	113.78	2.52	**116.30**
Domestic battery – flexibility services	138	14	152	15	1,263	109.24	11.19	**120.44**
Large scale battery	272,421	60,518	332,940	33,294	2,526,594	107.82	23.95	**131.77**
Diesel genset – back-up power	1,679,964	-	1,679,964	67,199	6,316,485	265.96	-	**265.96**
Diesel genset – flexibility services	1,679,964	35,956	1,715,920	68,637	6,316,485	265.96	5.69	**271.66**

Figure 10: A summary of the results of each technology use case

4. FINDINGS

DSO services have a carbon impact. The decision to procure a DSO service from any technology has an associated carbon impact and this impact varies with every technology and use case combination. The results show that this impact is between 7 and 272 grams of carbon dioxide equivalent per kWh of service provided, relative to a base case of not procuring the service. This study has not considered the carbon impact associated with alternative options to DSO services, such as investment in network infrastructure.

Operational emissions are the primary driver of carbon impact. The non-operational emissions allocated to the provision of DSO services are low, never exceeding one fifth of the total carbon impact. The low allocation of non-operational emissions directly reflects the low contribution of DSO services to an asset's total revenue stack.

- **Demand response (DSR) has the lowest impact of all technologies assessed at 7-68gCO2e/kWh.**

There are two primary reasons for this result:

- **Low or zero losses**: The losses associated with DSO service provision by DSR are low. Losses associated with DSR are also known as rebound losses, which describe the increase in total energy consumption that results from the demand response action.
- **Zero embodied emissions**: No embodied emissions are applied to DSR use cases because the assets either pre-exist or do not rely upon DSO services for their investment case.

Electric vehicle chargepoints are the leading low-carbon performer with an impact of just 7gCO_2e/kWh. There are no rebound losses associated with shifting EV charging demand; the total quantity of energy is needed to charge the car regardless of the time of day that this consumption takes place. The carbon impact derives solely from the difference in the carbon intensity of marginal grid generation during the response period and the period to which demand is shifted.

- **Domestic flexibility solutions generally have a low carbon impact. Next in the hierarchy after EV chargepoints are heat pumps, then domestic batteries.**

The primary driver of the difference between these three technologies is the effect of losses. There are no rebound losses associated with EV chargepoints, whereas demand response provided by shifting heat pump use requires an increase in total energy consumption if the core function of the technology (heating the home) is to be maintained. Domestic batteries show the highest losses of the three as a consequence of the round-trip efficiency of battery storage technology.

- **Currently battery projects have a mid-level carbon impact of 105-132gCO2e/kWh when using marginal grid carbon intensity data.**

This carbon impact is driven by losses. Round trip efficiency is the primary driver of the carbon impact of batteries. This is due to the low level of non-operational emissions (when allocated) and the minimal difference at present between the carbon intensity of the electricity imported and the grid generation that is offset.

Batteries have high non-operational emissions on a per MW basis. This can be attributed mainly to the energy intensive processes and raw materials that are required to produce battery cells. However, only a small proportion of these embodied and end-of-life emissions are attributed to the provision of DSO services because of the low contribution of DSO services to the total revenue of a battery project.

A carbon-optimised operational strategy could reduce the carbon impacts of batteries significantly. Battery assets have the luxury of choosing when they import energy from the grid. But the assumptions underpinning this work assume the battery use case is optimised for maximum financial returns, not lowest carbon impact. If appropriate incentives existed to incentivise battery operators to optimise for lower carbon, the results of this use case could be significantly different.

Embodied emissions drive the hierarchy. Within the different battery case studies non-operational emissions set the hierarchy of results. The domestic battery solar self-consumption use case has the lowest carbon impact of all battery use cases. This is because DSO services were assumed to not be a part of the investment case and so non-operational emissions are not applied. Between the other two battery use cases the large-scale battery has greater embodied emissions per kWh and thus a higher carbon impact; this could be attributed to technical differences such as battery chemistry and greater balance of plant requirements for large projects, or it could be an issue of data quality.

- **Natural gas turbines have a mid-level carbon impact of 116gCO$_2$e/kWh which is likely to increase over time.**

Operational emissions dominate the carbon impact. The long lifetime of gas turbines is and their relatively high direct emissions are the reason why operational emissions dominate the results for lifetime carbon impact. Embodied and end of life emissions are only produced once, so their effect is 'spread' over the whole lifetime of the asset.

Carbon impact is likely to increase over time. This use case is sensitive to future changes in the make-up of grid marginal generation. At present there is only a small difference between grid marginal carbon emissions and the emissions associated with burning natural gas. But in the future, as the most polluting generators are phased out, the carbon impact of providing DSO services from natural gas generators is likely to rise.

- **Diesel gensets have the highest carbon impact of all technologies, at 266-272gCO2e/kWh.**

Operational emissions dominate the carbon impact: Due to the high emissions associated with diesel fuel combustion and the long lifetime of the technology, embodied and end-of-life emissions make up only a very small part of the total carbon impact.

The result is sensitive to assumptions made on efficiency: The efficiency of the generator is a key assumption is this analysis. Assumptions have been made to be consistent with the low capacity factor at which the genset is likely to be running when providing DSO services.

Carbon impact is expected to rise in the future: As with natural gas generation, this use case is sensitive to future changes in the make-up of grid marginal generation. If the carbon intensity of grid marginal generation falls the carbon impact of this use case will worsen further.

- **Carbon assessments of DSO services are challenging and highly dependent on the data sources used.**

In general, assessing the carbon impact of flexibility services is challenging. This is due to the wide range of technologies providing DSO services, the variety of different use cases, challenges with the quality of available lifecycle assessment data, and the difficulty of appropriately allocating non-operational emissions.

The assessment of the carbon impact of landfill gas presents particular difficulties. Because it makes use of the polluting waste product of a separate industry, landfill gas generation is generally regarded as having very low carbon emissions. However, this result can only be reached if the scope of the assessment is extremely wide, taking account of the effects that would arise if the gas were not captured for generation use. Calculating the impact associated with DSO service provision adds another complexity by heightening the importance of the base case that the results are being measured against.

At present, there are only minor impacts associated with the difference in timing of import and export from the electricity grid. The results suggest that optimising the timing of import to periods of low marginal carbon intensity currently has a limited positive benefit. This conclusion can be traced back to the low daily variation in marginal grid carbon intensity in the national level data set used in this study.

Changes in marginal grid carbon intensity will benefit flexible technologies and disadvantage thermal generators. The different time scales over which this change can be experienced affect flexible technologies and thermal generators differently:

- **An increase in intra-day volatility could allow demand response and battery storage technologies to optimise their actions to reduce carbon impact.** An increase in the intra-day volatility of grid marginal carbon intensity could occur in the future. Including future projections of grid carbon intensity in this study would change the results by likely increasing the differential between the carbon intensity of the imported generation and that of the offset generation for DSR and battery storage. This work does not take account of the opportunity that these technologies have to optimise their behaviour to reduce carbon. An increase in the volatility of grid marginal carbon intensity would provide an opportunity for these technologies to optimise their behaviour to reduce carbon impact.
- **A fall in average annual gird marginal carbon intensity would disadvantage thermal generators.** The carbon impact of thermal generators would increase if the average grid marginal carbon intensity falls. This is because the carbon intensity of their source of energy (the combusted fuel) remains the same while the carbon intensity of the grid generation that they are offsetting reduces.

4.1 NEXT STEPS

The conclusions of this work present novel findings with implications for the treatment of carbon in flexibility markets. This is an area that is currently receiving considerable attention in the industry, with BEIS and Ofgem consulting on the next stage of their smart energy policy, with carbon in flexibility markets a core focus area. There are many areas where the work of Pro Low Carbon could be applied to ensure maximum impact and to help elevate the importance of carbon impact within flexibility service provision. These include:

- **Investigating the applicability of the methodology to all flexibility markets**. A key part of BEIS and Ofgem's work in this area is to develop an approach to carbon monitoring in flexibility markets. The methodology developed in Pro Low Carbon is specific to DSO services and local flexibility technologies, however it is likely to be applicable to wider markets with some adaption.
- **Embedding data transparency in flexibility markets.** Form recommendations on how to use the carbon assessment methodology developed in Pro Low Carbon to report on carbon intensity in flexibility markets. Reporting could start with DSO services but could later expand to cover wider energy flexibility markets. There should be a focus on both internal transparency, ensuring carbon data is available to those making procurement decisions, and external transparency, providing clarity on the carbon impact of services and sending signals on carbon impact to market participants.
- **Exploring how real time signals can help local flexibility market participants reduce their carbon impact.** WPD already provides a service reporting on the average carbon intensity of generation at a local level. This service could be built upon to help flexibility market participants to reduce their carbon impacts. This would involve understanding which signals are most useful to market participants and how these signals can be measured and communicated.
- **Monitoring the historical and ongoing carbon impact of WPD Flexible Power services.** Applying the Pro Low Carbon methodology to real historic dispatch and market participant data to understand the historical impact of DSO services.
- **Developing measures to reduce the carbon impacts of flexibility service procurement.** Understanding the scale of the carbon impacts from flexibility technologies is the first step towards developing effective measures to reduce them. BEIS and Ofgem are currently consulting on the effectiveness of measures that exist today and considering how a more robust mechanism could be developed that can be applied to all flexibility markets. The lessons learnt from Pro Low Carbon can provide vital input to this process.

The Pro Low Carbon methodology provides a useful starting point for understanding the carbon impact of flexibility services. Nevertheless, it could be developed to provide more accurate results and a deeper understanding of the different factors that influence the carbon impact of DSO services Areas for development could include:

- **Consideration of local level grid carbon intensity:** National level marginal grid carbon intensity data has been used in this work. This allows the results to be applied to many different areas, but there are scenarios where local level data would give more accurate results. For example, changes in demand or supply arising from DSO service provision could be met by local assets. However, local level effects are complex and require knowledge of precise asset locations, details of network constraints and an understanding of the behaviour of individual generators. WPD has laid down much of the foundation for a local level assessment of carbon impact with the Carbon Tracer Application, but some complex work remains.
- **Modelling carbon optimised import profiles:** The import profiles of demand response and battery technology use cases do not attempt to optimise their import timing to minimise carbon emissions. While there is currently no commercial incentive to do this, it is possible that certain domestic consumers may decide to operate their assets in this way. There is also the possibility in the future that firmer incentives to reduce carbon emissions could be introduced to energy markets. Technologies with the flexibility to decide when they import energy would stand to benefit from this and could further reduce their carbon impact.
- **Developing the methodology to apply to an even wider range of technology types:** This work has focussed on the primary technologies currently providing DSO services to WPD and those that are expected to do so in future. However, this does not cover the full spectrum of flexibility technologies and all the use cases that they can be deployed in. The methodology could be developed into a more universal framework to account for all possible forms of flexibility service provider.

5. APPENDIX A: LANDFILL GAS

5.1 CONTEXT

Landfill gas requires unique treatment because of its fuel source. This form of generation benefits from capturing and making use of a waste product of a separate industry. This waste product is a greenhouse gas that, unless captured, would be emitted directly into the atmosphere.

The common approach taken in carbon assessment is to adjust the methodology to take account of the fact that landfill gas is a waste product. The benefit of capturing and reusing a waste product should fall outside the core scope of most carbon assessment methodologies. However, it is common to treat landfill gas and other bioenergy as a special case and include these effects alongside the impacts of direct fuel combustion. As a result, the emissions from combustion and benefit of capturing the gas are assumed to cancel out and are considered to have a net-zero impact on carbon emissions.

This report attempts to take a consistent and fair approach to valuing carbon impact across different technology types. The scope boundary is set to include direct combustion emissions, emissions associated with electricity supply and non-operational carbon emissions associated with providing the DSO service.

Applying this approach directly would overlook a significant benefit of landfill gas. The environmental advantage of making use of what would otherwise have been a polluting waste product is significant. However, to include this effect, the approach of this study would have to be modified. But there are benefits associated with other technology classes that fall outside of the scope boundary, and the study has not been modified to take account of these. This includes the fact that technologies fuelled by renewable generation do not incur additional emissions from the extraction of fuels, unlike thermal generators. It is difficult to be completely consistent across all different technologies.

An additional complexity with landfill gas is the importance of the counterfactual. The common approach described above relies on the assumption that if the landfill gas were not used to generate electricity it would be spilt into the atmosphere. However, the business cases of most flexibility assets do not align with this assumption. It is unlikely that a landfill gas generator that was unsuccessful in obtaining a contract to provide a DSO service would then release the fuel that it would have used to provide that service into the atmosphere. The more likely scenario is that the asset would provide another service instead such as selling its generation in the wholesale markets. This idea of ‘what the asset would be doing otherwise’ is crucial.

The inconsistency of existing approaches and the special importance of the counterfactual to DSO service provision means assessing the carbon impact of landfill gas in this work is difficult. For this reason landfill gas has been excluded from the headline results. Two different approaches for assessing landfill gas generators have been explored in this section.

5.2 METHODOLOGY

Two different approaches are taken in the assessment of the carbon impact of landfill gas. These approaches differ only in their approach to operational emissions. The key assumption that accounts for the effects described above is the fuel emissions factor of landfill gas.

- **Option 1 – include direct emissions:** Set the fuel emissions factor equal to its true value for landfill gas. This is consistent with an assumption that the fuel would be used to power the generator for another use if it were not burnt to provide the DSO service.
- **Option 2 – exclude direct emissions:** Set the fuel emissions factor equal to zero. This is consistent with an assumption that landfill gas would otherwise be spilt into the atmosphere if not used to provide the DSO service.

5.3 RESULTS

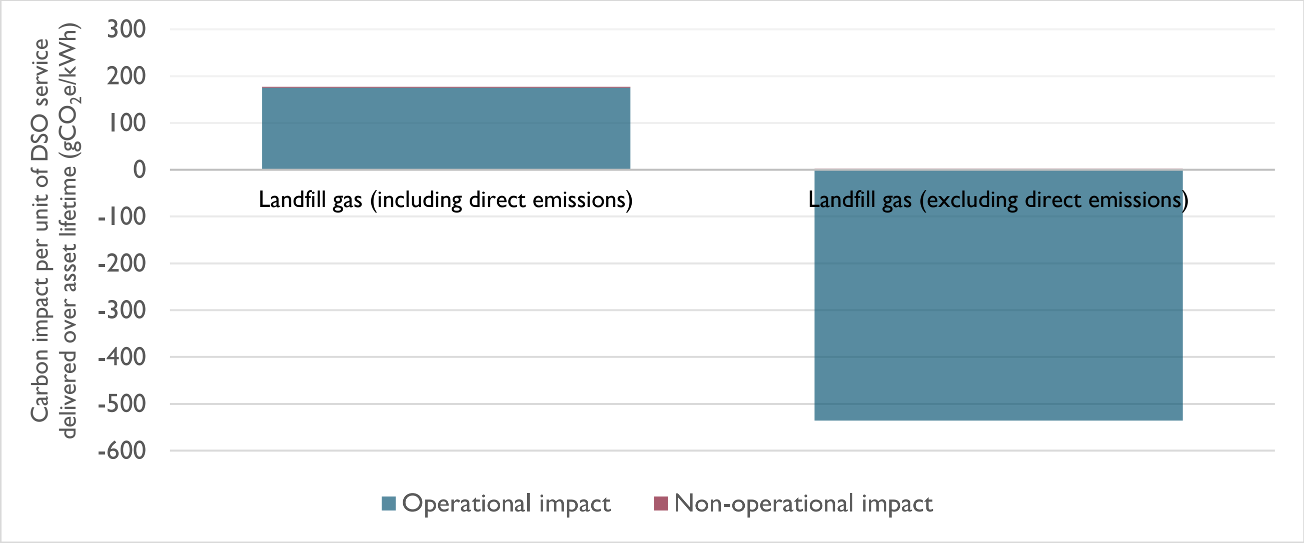

Figure 11: The results of two different approaches for calculating the carbon impact of landfill gas turbines

Technology use case	Operational lifetime emissions	Non-op allocated lifetime emissions	Total lifetime emissions	Total annual emissions	Volume of DSO service provided	Lifetime OP emissions per kWh of DSO service	Lifetime NON-OP emissions per kWh of DSO service	Lifetime emissions per kWh of DSO service
	[kgCO2e]	[kgCO2e]	[kgCO2e]	[kgCO2e]	[kWh]	[gCO2e/kWh]	[gCO2e/kWh]	[gCO2e/kWh]
Landfill gas (including direct emissions)	1,104,453	15,901	1,120,354	44,814	6,316,485	174.85	2.52	177.37
Landfill gas (excluding direct emissions)	-3,385,225	15,901	-3,369,324	-134,773	6,316,485	-535.94	2.52	-533.42

Figure 12: A summary of the results for the two landfill gas calculation approaches

5.4 FINDINGS

Excluding direct emissions from the study returns a negative carbon impact from providing DSO services from a landfill gas generator. This means that there is a net reduction in electricity system carbon emissions relative to the asset not providing the service. This result is a direct consequence of the assumption that if the asset were not providing the service the gas would instead be released to the atmosphere.

If direct emissions are included, landfill gas has a high carbon impact. The technology has a greater carbon impact per kWh of DSO service provided than all DSR use cases, all battery use cases, and the use case of a gas turbine burning natural gas. Only diesel generators have a more significant carbon impact.

Direct emissions of landfill gas combustion are greater than natural gas combustion. This result is driven by the higher fuel emissions factor of landfill gas.

In both scenarios non-operational emissions are very small. Regardless of the approach taken with the direct emissions of landfill gas combustion, the operational emissions over the lifetime of the asset providing the DSO service far exceed the embodied and end-of-life emissions of the gas turbine. That can be allocated to the provision of the DSO service.

The complexity of assessing the carbon impacts of landfill gas illustrates the importance of well-defined emissions boundaries and assumptions in carbon assessments. The example of landfill gas shows that different approaches can lead to dramatically different results. It is important to understand exactly what should be treated as in scope and if any exceptions can be applied for special cases. The fine details can have a big impact of the headline results.

6. APPENDIX B: MODELLING ASSUMPTIONS

	TECHNOLOGY USE CASE			TECHNICAL DETAILS				
	Asset type	Use case	Non-op. emissions	Capacity (MW)	Energy source	Import timing	Losses/rebound effect	Lifetime (years)
1a	Domestic battery	Increases self-consumption of rooftop solar and provides back up power	Excluded	0.005	Rooftop solar generation during the day	11:00 – 16:00	16%[4]	10
1b		Managed by an energy flexibility aggregator to provide ancillary services to the ESO and DSO	Included	0.005	Overnight import from the electricity grid	00:00 – 04:00	16%[4]	10
2	Large scale battery	Provides electricity market services including energy trading and ancillary services to the ESO and DSO	Included	10	Evening import from the electricity grid	20:00 – 21:00	16%[4]	8
3	Demand response (commercial)	Non electricity market use (temperature-controlled storage)	Excluded	1	Grid import (time-shifted)	20:00 – 00:00	10%[4]	10
4	Demand response (domestic heat pump)	Non electricity market use (domestic heating)	Excluded	0.003	Grid import (time-shifted)	06:30 – 08:30, 20:00 – 22:00	10%[4]	10
5	Demand response (EV charger)	Non electricity market use (EV charging)	Excluded	0.007	Grid import (time-shifted)	20:00 – 04:00	0%	10
6a	Diesel genset	Provides back up power to onsite energy consumer	Excluded	10	Combustion of diesel fuel	N/A	N/A	25
6b		Provides electricity market services including energy trading and ancillary services to the ESO and DSO	Included	10	Combustion of diesel fuel	N/A	N/A	25
7	Gas turbine (natural gas)	Provides electricity market services including energy trading and ancillary services to the ESO and DSO	Included	10	Combustion of natural gas	N/A	N/A	25
8	Gas turbine (landfill gas)	Provides electricity market services including energy trading and ancillary services to the ESO and DSO	Included	10	Combustion of landfill gas	N/A	N/A	25

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[4] Assumptions based on Everoze internal knowledge

	TECHNOLOGY USE-CASE	FINANCIAL					NON-OP. EMISSIONS (NON-ALLOCATED)		OPERATIONAL EMISSIONS	
	Asset type	CapEx (£)	OpEx (£/year)	DSO revenue (£/MW/year)	WACC (%)	Target IRR (%)	Embodied carbon (kgCO2e)	End-of-life carbon (kgCO2e)	Fuel emissions factor (gCO2e/kWh)	Generator efficiency (%)
1a	Domestic battery	N/A	N/A	N/A	8%	10%	N/A	N/A	N/A	N/A
1b		£7,532	£0	£6,000	8%	10%	673	125	N/A	N/A
2	Large scale battery	£5,500,000	£82,500	£6,000	8%	10%	1,083,000	125,000	N/A	N/A
3	Demand response (commercial)	N/A	N/A	N/A	8%	10%	N/A	N/A	N/A	N/A
4	Demand response (domestic heat pump)	N/A	N/A	N/A	8%	10%	N/A	N/A	N/A	N/A
5	Demand response (EV charger)	N/A	N/A	N/A	8%	10%	N/A	N/A	N/A	N/A
6a	Diesel genset	N/A	N/A	N/A	8%	10%	N/A	N/A	240.57[5]	30%[6]
6b		£4,720,691	£118,017	£6,000	8%	10%	478,000	23,665	240.57[5]	30%[6]
7	Gas turbine (natural gas)	£7,081,036	£118,017	£6,000	8%	10%	318,000	23,665	183.87[5]	28%[7]
8	Gas turbine (landfill gas)	£7,081,036	£118,017	£6,000	8%	10%	318,000	23,665	199.02[4] or 0	28%[6]

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[5] UK Government GHG Conversion Factors for Company Reporting 1.0, Full Set, 2020

[6] Benton, 2016, 'A Life Cycle Assessment of a Diesel Generator Set' and Shakti Sustainable Energy Foundation, ‘Diesel Generators: Improving Efficiency and Emission Performance in India’

[7] Sri Hapsari Budisulistiorini et al., 2007, ‘Energy Generation from Landfill Gas’