# Muir Mhòr Offshore Wind Farm

## Environmental Impact Assessment Report

### Volume 3, Appendix 18.1: Greenhouse Gas Assessment Technical Report

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# Glossary

| Term | Definition |
|---|---|
| Developer | Muir Mhòr Offshore Wind Farm Limited |
| Floating Foundations | The floating structures on which the Wind Turbine Generators are installed. |
| Floating anchors | The structures which anchor the Floating Foundations to the seabed, connected to the foundation mooring. |
| Foundation mooring | The mooring structures which connect the Floating Foundations to the anchors. |
| Inter-array cables | Cables which link the wind turbines generators to each other and the Offshore Electrical Platform(s). |
| Landfall | The area between Mean High Water Springs (MHWS) and Mean Low Water Springs (MLWS) where the offshore export cables are brought onshore. |
| Offshore Electrical Platform (OEP) | Offshore platform consisting of High Voltage Alternating Current (HVAC) equipment, details depending on the final electrical set up of the Project. |
| Offshore Export Cable Corridor (ECC) | The area within which the offshore export cables will be installed. |
| Offshore export cables | The subsea electricity cable circuits running from the Offshore Electrical Platform(s) to the landfall which will transmit the electricity generated by the offshore wind farm to the onshore export cables for transmission onwards to the onshore substation and the national electrical transmission system along with auxiliary cables such as fibre optic cables. |
| Project | Muir Mhòr Offshore Wind Farm – comprises the wind farm and all associated offshore and onshore components. |
| Proposed Development | The offshore Muir Mhòr Offshore Wind Farm project elements to which this Offshore EIA Report relates. |
| Wind Turbine Generator (WTG) | The wind turbines that generate electricity consisting of tubular towers and blades attached to a nacelle housing mechanical and electrical generating equipment. |

# Acronyms

| Term | Definition |
|---|---|
| AR5 | Fifth Assessment report |
| AR6 | Sixth Assessment Report |
| BEIS | Department for Business, Energy and Industrial Strategy |
| ECC | Export Cable Corridor |
| CaP | Cable Plan |
| CCGT | Combined Cycle Turbine |
| CCR | Climate Change Resilience |
| CFD | Contracts for Difference |
| CI | Confidence Interval |
| CMIP6 | Coupled Model Intercomparison Project Phase 6 |
| CO2e | Carbon dioxide equivalents |
| CoP | Construction Programme |
| DESNEZ | Department for Energy Security and Net Zero |
| DNV | Diet Norske Veritas |
| DUKES | Digest of UK Energy and Statistics |
| ECC | Export Cable Corridor |
| EIA | Environmental Impact Assessment |
| FMMS | Fisheries Management and Mitigation Strategy |
| FTE | Full Time Employee |
| GHG | Greenhouse Gas |
| gCO2/kWh | Grams of CO2/kilowatt hours |
| GW | Gigawatt |
| GWP | Global Warming Potential |
| GWP100 | Average Global Warming Potential Over 100 Years |
| GWh/yr | Gigawatt hour per year |
| HVAC | High Voltage Alternating Current |
| hr | Hour |
| IAC | Inter-array Cable |
| ICCI | In-Combination Climate Impacts |
| ICCP | Impressed Current Cathodic Protection |
| IEMA | Institute of Environmental Management and Assessment |
| IPCC | Intergovernmental Panel on Climate Change |
| IPCC AR5 | Intergovernmental Panel on Climate Change Fifth Assessment Report |
| IPCC AR6 | Intergovernmental Panel on Climate Change Sixth Assessment Report |
| ISO | International Standards Organisation |
| kWh | Kilowatts per Hour |

| Term | Definition |
|---|---|
| Ktkm | Thousands of tonne-kilometres |
| LCA | Life Cycle Assessment |
| LSE | Likely Significant Effects |
| MD-LOT | Marine Directorate – Licensing Operations Team |
| MHWS | Mean High Water Springs |
| MLWS | Mean Low Water Springs |
| MMOWF Ltd | Muir Mhòr Offshore Wind Farm Limited |
| MPS | Marine Policy Statement |
| MSL | Mean Sea Level |
| MW | Megawatt |
| NMP | National Marine Plan |
| NPF4 | National Planning Framework 4 |
| NSIP | Nationally Significant Infrastructure Projects |
| NSP | Navigational Safety Plan |
| OEP | Offshore Electrical Platform |
| O&M | Operation and maintenance |
| OnSS | Onshore Substation |
| OSS | Offshore Substation |
| OWF | Offshore Wind Farm |
| PEMP | Project Environmental Monitoring Programme |
| PO | Plan Option |
| RCP | Representative Concentration Pathways |
| t | Tonne |
| TJ | Terajoules |
| tkm | Tonne-kilometre |
| VMP | Vessel Management Plan |
| WTG | Wind Turbine Generator |

# 1. INTRODUCTION

1.1.1. Muir Mhòr Offshore Wind Farm Limited (the Developer) is proposing to develop Muir Mhòr Offshore Wind Farm (OWF) (hereafter referred to as the Project). The Project is made up of both offshore and onshore components. The offshore infrastructure of the Project seaward of Mean High-Water Springs (MHWS) is hereafter referred to as 'the Proposed Development'.

1.1.2. Since the industrial revolution, humans have accelerated the release of previously stored carbon (in the form of carbon dioxide) and other gases into the atmosphere, where they act to trap heat and cause global warming. Climate change is the term for this long-term rise in average temperatures, which is also associated with changes to global weather patterns.

1.1.3. This document presents the results of the Environmental Impact Assessment (EIA) process to determine the potential impacts of the Project on climate change. Specifically, this document considers the potential impacts from the construction, Operation and Maintenance (O&M), and decommissioning of the Wind Turbine Generators (WTGs), Offshore Electrical Platform (OEP), offshore export cables, onshore cable infrastructure and Onshore substation (OnSS).

1.1.4. The climate change impacts of a product, process, service or installation can be determined using a technique known as Life Cycle Assessment (LCA). The International Standards Organisation (ISO), in its series ISO 14040-44, defines LCA to be the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle", and outlines the four-step method adopted for this analysis. The sections that follow cover each of these steps in turn, explaining:

- Setting the system boundary to define the scope of work;
- Collecting the necessary data for the modelling;
- Bringing together the flow data and characterisation factors; and
- Interpreting and reporting the results.

1.1.5. The relative contributions that different so-called Greenhouse Gases (GHGs) make towards climate change are denoted by the Global Warming Potential (GWP) of each gas, relative to the chosen reference gas, carbon dioxide. Because the gases dissipate at different rates in the atmosphere, the GWP of gases varies according to the timeframe of the analysis. Whilst datasets exist for GWP over 20-year and 500-year timeframes, the usual basis for international analysis and reporting is 100-years (GWP100).

1.1.6. Within this timeframe, the United Nations Intergovernmental Panel on Climate Change (IPCC) has published a series of Assessment Reports to provide the latest scientific opinion on the GWP factors that should be used. The most recently issued preliminary GWP results are from the Sixth Assessment Report (AR6), however, the latest UK government carbon reporting factors for 2023 are currently based on Fifth Assessment Report (AR5; UN IPCC, 2013), and so the GWP factors used in this report are based on that report and are presented below. Table 1-1 lists all the gases that contribute to the total reported, and no significant emissions are thought to be excluded from the calculations.

Table 1-1 GWP100 factors (from AR5) used in this analysis

| Greenhouse gas | GWP100 factor (in kg $CO_{2e}$ per kg) |
|---|---|
| Carbon dioxide ($CO_2$) | 1 |
| Methane ($CH_4$) | 28 |
| Nitrous Oxide ($N_2O$) | 265 |
| Sulphur Hexafluoride ($SF_6$) | 23,500 |

# 2. SETTING THE GOAL AND SCOPE FOR ANALYSIS

2.1.1. The first step was to agree the goal and scope for the analysis, defining what would be within the scope of study and what would not. The topics and the decisions agreed are summarised in Table 2-1.

Table 2-1 Scope of Analysis

| Topic | Decision |
|---|---|
| **Study goal:** | To determine the GHG emissions from the lifetime operations of the Project, and to compare them with emissions that would otherwise arise from generating the same electricity. |
| **Scenarios:** | Four scenarios, considering deployment of two turbine sizes and two foundation types. |
| **Time:** | Based in the near present and so using current estimations of material production impacts. |
| **Geography:** | Located in Scotland, but also cognisant of materials sourced from around the world. |
| **Functional unit:** | Calculations to initially determine the total emissions across the lifetime of the installation, then factor in the total electricity produced to scale emissions to a carbon intensity of generation, in grams of CO2/kilowatt hours (gCO2/kWh). |
| **Impact criteria:** | Only global warming potential (climate change) over a 100-year timeframe was considered in this study. |
| **Data sources:** | Detailed in Section 3 – a combination of primary data from the developers and literature data. |
| **Life-cycle stages:** | All life cycle stages, from cradle to grave. |

# 3. DATA COLLECTION

3.1.1. Data collection is the most challenging aspect of an LCA study. Looking to model the entire burdens of an offshore wind farm before, during and after an assumed 35 years of operation is a challenge, and involves collecting data from the across six key stages of the life cycle:

- Raw Materials;
- Manufacturing;

- Installation;
- Operation;
- Freight; and
- End of Life.

3.1.2. The rest of this section provides more detail on the data collected for each of the six stages. The primary source of data for the Project was information regarding the planning design and construction of the wind farm that has also been used to inform the EIA process to date for the Project.

## 3.2. RAW MATERIALS

3.2.1. 'Raw Materials' refers to the environmental impacts embedded in the materials of construction of the windfarm (but not their fabrication or installation, which are covered in later stages). The Developer provided details of the materials that are expected to be needed for, for example, the WTGs. This information was supported with data provided in a bespoke template, on the amounts of materials expected to be used in the construction. The materials associated with the onshore substation are deemed sufficient to accommodate a fully enclosed substation which would be the reasonable worst case for embodied carbon. The main components and weights are listed in Table 3-1. For the purposes of undertaking a robust, conservative analysis, it was assumed that none of these materials would contain recycled content, instead being from newly extracted materials.

3.2.2. Two potential scenarios are presented for the Project, both in terms of the WTG count and the foundation construction, representing the range of potential life cycle impacts. For the WTG count scenarios, 'Scenario 1' consists of 44 larger 23-megawatt (MW) WTGs, while 'Scenario 2' consists of 67 smaller 15 MW WTGs. Additionally, there are two foundation scenarios, with the foundations being constructed using either steel or concrete.

*Table 3-1 Main materials in the Muir Mhòr components, and their amounts (indicative values)*

| Description | Detail | Scenario 1 | Scenario 2 | Units |
|---|---|---|---|---|
| WTG Tower | Steel | 52,800 | 60,300 | tonnes (t) |
| | Aluminium | 4,400 | 6,700 | t |
| WTG Blades | Carbon fibre | 13,200 | 20,100 | t |
| | Wood | 1,056 | 1,608 | $m^3$ |
| WTG Nacelle | Copper | 4,400 | 6,700 | t |
| | Steel | 52,800 | 46,900 | t |
| | Oil & Grease | 1 | 2 | t |
| WTG | Cast Iron | 19,800 | 30,150 | t |
| | Cromag Steel | 8,800 | 13,400 | t |
| | Polymer | 440 | 670 | t |

| Description | Detail | Scenario 1 | Scenario 2 | Units |
|---|---|---|---|---|
|  | Neodymium | 880 | 1,340 | t |
| Fluids & Gases (WTG) | Oil & Grease | 3,201 | 4,874 | t |
|  | Nitrogen | 7,451 | 11,346 | t |
|  | Battery | 176 | 268 | t |
| WTG Foundation - steel | Steel | 321,200 | 355,100 | t |
|  | Polyester Rope | 13,200 | 20,100 | t |
| WTG Foundation – concrete | Concrete | 140,800 | 670,000 | m³ |
|  | Steel | 140,800 | 180,900 | t |
|  | Polyester Rope | 5,280 | 8,040 | t |
| WTG Foundation - anchors | Steel | 79,200 | 120,600 | t |
|  | Cement | 52,800 | 80,400 | t |
| OEP Foundation | Steel | 22,400 | 19,800 | t |
|  | Cement | 2,400 | 4,800 | t |
| Inter-array cables | Steel | 5,000 |  | t |
|  | Copper | 7,500 |  | t |
|  | Plastic | 3,000 |  | t |
| Offshore export cables | Copper | 14,850 |  | t |
|  | Lead | 5,400 |  | t |
|  | Steel | 10,800 |  | t |
|  | Plastic | 8,100 |  | t |
| Landfall cables | Copper | 585 |  | t |
|  | Lead | 270 |  | t |
|  | Steel | 990 |  | t |
|  | Plastic | 1,863 |  | t |
| OEP Substation | Steel | 20,000 | 15,000 | t |

| Description | Detail | Scenario 1 | Scenario 2 | Units |
|---|---|---|---|---|
|  | Copper | 1,000 | 750 | t |
|  | Plastic | 100 | 50 | t |
|  | Wood | 800 | 400 | m³ |
|  | Glass | 100 | 50 | t |
| Fluids & Gases (OEP) | Oil & Grease | 1,253 | 628 | t |
|  | Diesel | 249 | 125 | t |
|  | SF6 | 5 | 4 | t |
|  | Battery | 4 | 2 | t |
|  | Water | 12 | 6 | t |
| OEP Topside | Equipment | 3,000 | 1,500 | t |
|  | Structural Steel | 1,800 | 900 | t |
|  | Insulation | 60 | 30 | t |
|  | Cables | 200 | 100 | t |
|  | Steel | 8,600 | 4,300 | t |
| Onshore cable | Steel | 3,240 |  | t |
|  | Copper | 3,960 |  | t |
|  | Plastic | 2,448 |  | t |
| Onshore export cables | Steel | 5,670 |  | t |
|  | Lead | 3,375 |  | t |
|  | Copper | 4,050 |  | t |
|  | Plastic | 7,452 |  | t |
| Transition Joint Bay | Concrete | 1,000 | 1,500 | m³ |
|  | Steel | 100 | 150 | t |
| Onshore Substation | Concrete | 8,000 |  | m³ |
|  | Fill | 159,600 |  | t |

| Description | Detail | Scenario 1 | Scenario 2 | Units |
|---|---|---|---|---|
| | Fencing | 3 | | t |
| | Reinforcement | 600 | | t |
| | Chippings | 6,048 | | t |
| | Drainage | 2 | | t |
| | Structural Steel | 1,200 | | t |
| | Cladding | 6,000 | | m² |
| | Asphalt | 7,000 | | m³ |
| | Steel | 500 | | t |
| | Rebar | 700 | | t |
| | Loose aggregate | 9,240 | | t |

## 3.3. MANUFACTURING

3.3.1. Some of the values in the above section simply cover the production of, for example, a tonne of steel. Further emissions are embedded during the manufacturing of the wind farm components from those materials. From SLR's experience, it is not practical to gather actual manufacturing data for all components, and many would make a negligible contribution to the final impacts, but it was deemed appropriate to estimate the manufacturing burdens for some of the materials, as detailed in Table 3-2. The quoted weights were deduced from all the data described above and are presented for the two scenarios and foundation types described in the Raw Materials section.

*Table 3-2 Materials weights separately assigned manufacturing burdens*

| Description | Detail | Scenario 1 (steel foundation) | Scenario 1 (concrete foundation) | Scenario 2 steel foundation) | Scenario 2 (concrete foundation) | Units |
|---|---|---|---|---|---|---|
| Metal working | Aluminium | 4,400 | | 6,700 | | t |
| | Copper | 36,345 | | 38,395 | | t |
| | Lead | 9,045 | | 9,045 | | t |
| | Cast Iron | 19,800 | | 30,150 | | t |
| | Steel | 596,403 | 416,003 | 665,153 | 490,953 | t |
| Plastic pipe production | Polyethylene | 2 | | 2 | | t |
| Glass tempering | Glass | 100 | | 50 | | t |

## 3.4. INSTALLATION

3.4.1. Installation covers the extensive effort associated with constructing the Project. The typical expected consumption and use data for the different aspects of installation are presented in Table 3-3 below.

*Table 3-3 Installation stages separately assigned burdens*

| Description | Detail | Scenario 1 | Scenario 2 | Units |
|---|---|---|---|---|
| **Construction Transport** | Helicopter movements | 52 | 156 | hour (hr) |
| | Vessel movements | 6,750,000 | 6,750,000 | tonne-kilometre (tkm) |

## 3.5. OPERATION AND MAINTENANCE

3.5.1. During operation of the Project, many trips will again be needed to keep the installation in good working order. The anticipated transportation movements across the operational phase of the Project are summarised in Table 3-4.

*Table 3-4 Vessel activities during operation and maintenance (Across Lifetime)*

| Description | Detail | Scenario 1 | Scenario 2 | Units |
|---|---|---|---|---|
| **O&M Transport** | Vessel movements | 1,311 | 1,311 | TJ diesel |
| | Helicopter movements | 79,374 | 79,374 | hr |
| | Drone movements | 882,000 | 882,000 | km |
| | Vehicle movements | 7,280 | 7,280 | km |

3.5.2. It is anticipated that maintenance work will include regular replacement of various materials. Since no detailed maintenance data was available, an additional 2% of all raw materials and manufacturing processes to construct the Project are assumed to be required for maintenance/replacement across the lifetime of the Project.

3.5.3. It is also anticipated that to enable its efficient operation, the Project will consume a relatively low level of grid electricity. There is some uncertainty about the level involved, however the estimate used in these calculations is 110 kWh per turbine, informed by consumption figures from other offshore wind farms in the UK.

## 3.6. FREIGHT

3.6.1. In addition to the vessel movements already described, the calculations consider the freight that will bring the construction and maintenance materials to the local area, and (at end of life) remove the materials for recycling or disposal. As mentioned in Table 2-1, at this stage these distances are based on indicative distances and locations. The estimated total additional amounts of freight movements required, in thousands of tonne-kilometres (ktkm) by road and by sea, are presented in Table 3-5, for the two scenarios and foundation types described in paragraph 3.2.2.

*Table 3-5 Additional anticipated freight requirements*

| | Road ktkm | | | | Ship ktkm | | | |
|---|---|---|---|---|---|---|---|---|
| | **Scenario 1 (steel foundation)** | **Scenario 1 (concrete foundation)** | **Scenario 2 (steel foundation)** | **Scenario 2 (concrete foundation** | **Scenario 1 (steel foundation)** | **Scenario 1 (concrete foundation)** | **Scenario 2 (steel foundation)** | **Scenario 2 (concrete foundation)** |
| Raw Materials | 342,568 | 625,090 | 387,889 | 783,621 | 19,520,380 | 35,619,205 | 22,102,866 | 44,652,715 |
| Use | 5,580 | | 5,580 | | 317,957 | | 317,957 | |
| End of Life (Decommissioning) | 33,981 | 24,626 | 37,898 | 28,874 | 0 | | 0 | |

## 3.7. DECOMMISSIONING (END OF LIFE)

3.7.1. It is difficult to be certain what will happen to the Project's materials at end of life, simply because this will not occur for another 35 years, by which time, the state of available technology may be very different. However, the choice of the "cut-off" approach for accounting for recycled content and recycling means this is less critical.

3.7.2. In that accounting framework, the Project could be given credit for any recycled materials used in its lifetime, as these (typically) contain less embedded carbon than the unprocessed materials they replace. As described in the raw materials section above however, it has been assumed that all materials are unprocessed to perform a robust assessment. At the end of their life, the materials must be managed until they are either disposed of or recycled.

3.7.3. For wind turbine infrastructure, this means that the transport elements at end of life must be included, but once the materials reach the point where they are ready to be recycled, they exit the analysis boundary of this report and are not considered further. Moreover, for the materials that are landfilled, associated emissions should be included, however it is anticipated there should be little if any emissions from the inert materials whilst in landfill. This is due to low/no decomposition of organic material, so the burden is reduced to the freight impacts mentioned above.

# 4. LIFE CYCLE IMPACT ASSESSMENT

4.1.1. By bringing together all the above information, and applying appropriate characterisation factors, an initial estimation was calculated for the GHG emissions of the Project.

## 4.2. CHARACTERISATION FACTORS

4.2.1. Three sources were used to estimate the unit impacts of the different flows required across the lifetime model of the wind farm, as follows:

- The UK Government's "conversion factors for company reporting of greenhouse gas emissions" was used for marine gas oil (as well as some energy unit conversions and waste management processes). These are themselves based on the Fifth Assessment Report (AR5) from the International Panel on Climate Change (IPCC);
- The University of Bath's Inventory of Carbon and Energy (Hammond and Jones, 2008) dataset was used for a characterisation factor for asphalt; and
- An article published in ScienceDirect detailing a study on the emissions of drones was used to calculate a characterization factor for drone use (Rodrigues *et al*., 2022); and
- All the remaining characterisation factors were taken from the ecoinvent database (Ecoinvent, 2016). To ensure consistency with the UK Government's data, the method used was the same IPCC2013 data from the AR5 report.

4.2.2. This selection of sources for the characterisation factors means that all impacts are reported as emissions of greenhouse gases that contribute to climate change, considered over a 100-year period, relative to the impact of carbon dioxide i.e.in units of weight of Carbon Dioxide equivalents (CO2e).

## 4.3. CLIMATE CHANGE RESULTS

4.3.1. Applying the chosen characterisation factors to the inventory of flows generated during the data collection, and summing by life cycle stage, led to the compilation of the initial results presented in Table 4-1.

*Table 4-1 Climate change impact (in t CO2e) contributions from each life cycle stage*

| Life Cycle Stage | Scenario 1 (steel foundation) | Scenario 1 (concrete foundation) | Scenario 2 (steel foundation) | Scenario 2 (concrete foundation) |
|---|---|---|---|---|
| Raw Materials | 3,018,000 | 2,784,000 | 3,911,000 | 3,728,000 |
| Manufacture | 1,354,000 | 985,000 | 1,501,000 | 1,145,000 |
| Transport | 261,000 | 471,000 | 293,000 | 589,000 |
| Installation | 0 | 0 | 0 | 0 |
| Use | 297,000 | 285,000 | 318,000 | 307,000 |
| End Of Life | 0 | 0 | 0 | 0 |
| Total | 4,930,000 | 4,525,000 | 6,023,000 | 5,769,000 |

4.3.2. The results show that the Project's materials (and their manufacture) make the largest contribution (ranging from 83% to 90% across the scenarios) to the overall impacts. In contrast, despite the large quantum of fuel consumption from vessel movements throughout the lifetime, the impacts from transport are relatively insignificant accounting for 5-10% of the respective overall impacts.

4.3.3. Table 4-1 also shows that a smaller number of large WTGs (Scenario 1) has a lesser carbon impact compared to a larger number of smaller WTGs (Scenario 2). Additionally, the concrete foundations have a lesser carbon impact than the steel foundations. Therefore, the "best" scenario is the smaller number of large WTGs and concrete foundations, whereas the "worst" scenario is the larger number of small WTGs with steel foundations. We see a c. 30% difference between the best and worst scenarios.

## 4.4. CARBON INTENSITY CALCULATION

4.4.1. Looking at the worst-case scenario, Scenario 3 with steel foundations, 6.0 Million tonnes (Mt) CO2e is a significant amount of carbon emissions for the Project over its lifetime, but this should be assessed in the context of the electricity it will generate. There are uncertainties about how much electricity will be generated (these are explored later in Section 4.7.1), however it is estimated that its annual production levels might be of the order of 4,650 GWh/yr. This is estimated based on the wind turbine sizes and numbers for which the emissions have been calculated, and using a load factor of 52.9%, which is the mid-point of the range (52.9% ± 6.9%) offered in a study for UK Government (Det Norske Veritas (DNV) GL Energy, 2019). Ultimately the actual number of turbines could be lower, which would reduce the annual production levels, although embedded carbon emissions would also reduce in this scenario. Running at this rate for 35 years, the Project will generate 163,000 GWh of electricity over its lifetime. Dividing the aforementioned 6.0Mt CO2e of carbon emissions (for the worst-case scenario) across this electricity generated yields the average carbon intensity of the electricity over the Project’s lifetime:

$$Carbon\ Intensity = \frac{Lifetime\ carbon\ emissions}{Lifetime\ electricity\ generated} = \frac{6.0\ \mathrm{Mt}}{163{,}000\ \mathrm{GWh}} = 36.9g\ CO2e/kWh$$

4.4.2. For the best-case scenario, Scenario 1 with concrete foundations and the DESNZ load factor, more electricity is estimated to be produced each year (5,500 GWh), and the total carbon footprint is 4.9 Mt. Together, these years have an average carbon intensity of 23.7g CO2e/kWh.

## 4.5. PAY BACK PERIOD

4.5.1. It is common practice to determine a wind farm’s carbon “pay-back” period – that is, how long into the lifetime of the wind farm before the carbon emissions associated with its construction are counter-acted by the lower carbon emissions of the electricity it generates. To perform this calculation, it is necessary to determine how the electricity would otherwise be generated. It is accepted that when the wind farm comes online, its additional electricity will not replace nuclear or other renewable generating technologies. Rather, it will displace whatever generation technology would have been “the last to be turned on”. Not the grid mix therefore, but the so-called “marginal mix”. In the UK, for the foreseeable future, the marginal mix technology is expected to be gas, namely Combined Cycle Gas Turbine (CCGT) which has a carbon intensity of about 371 g/kWh (Digest of UK Energy and Statistics (DUKES), 2023). Alternatively, RenewableUK recommends (Renewable UK, n.d.) using the DUKES “all non-renewable fuels” (coal, oil, gas and other solid fuels including non-renewable waste) emission factor of 424 g/kWh[1].

4.5.2. Multiplying these intensities by the 4,650 GWh of electricity generated each year (for the worst-case scenario) reveals that the counterfactual-sourced electricity would be responsible for 1.7 Mt CO2e (CCGT) or 2.0 Mt CO2e (all non-renewables) each year. The cumulative effect of this over the first four years of operation is compared in Figure 4.1 with the total lifetime emissions for the Project. As the annotation shows, under the assumptions outlined above, the Project would be expected to achieve carbon payback in between 3.1-3.5 years (and then deliver annual savings for each of the following years of operation).

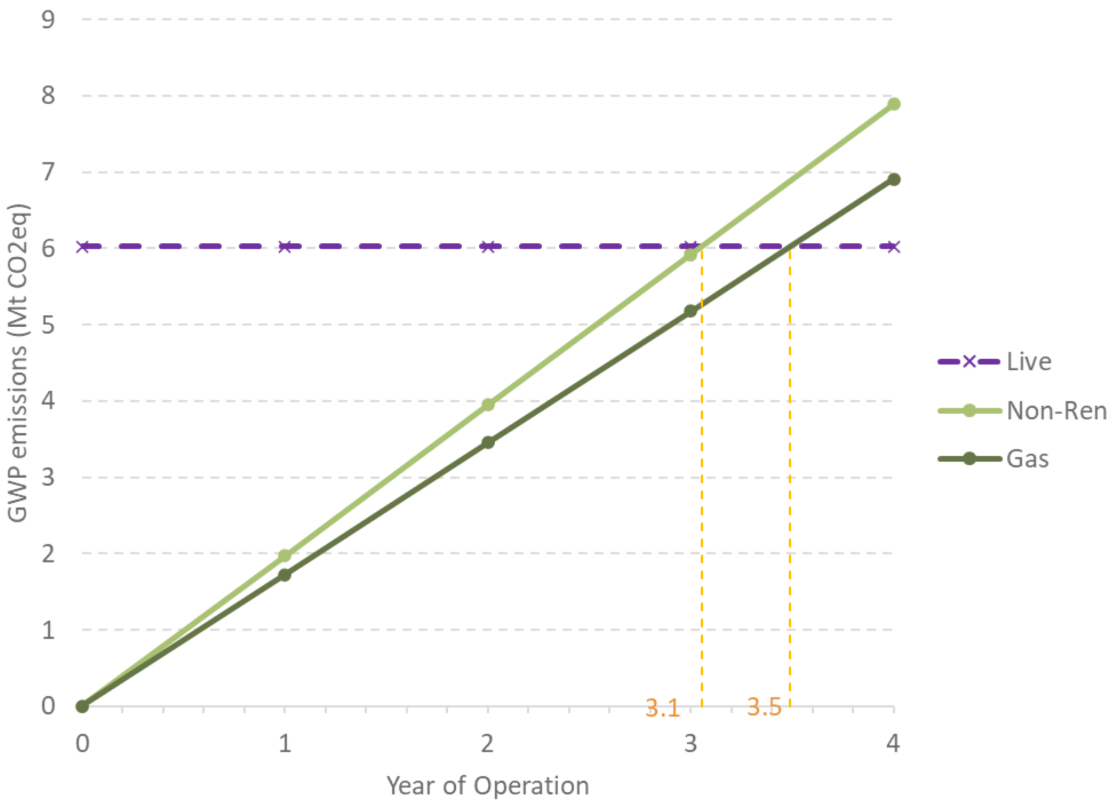

*Figure 4.1 GWP “Pay Back” Analysis for the worst-case scenario (Scenario 2 with steel foundations)*

4.5.3. Another way of looking at this is to determine the cumulative impacts of 35 years of the alternative electricity sources. These turn out to be 60 Mt CO2e (CCGT) or 69 Mt CO2e (all non-renewables), between 10 and 11 times the lifetime carbon emissions of (the worst-case scenario for) the Project, depending on the alternative electricity source.

4.5.4. Overall, the Project’s worst-case scenario is deemed to have a significant net benefit regarding lifetime emission reduction compared to the project baseline scenarios, with a net benefit of 54 Mt CO2e assuming CCGT and 63 Mt CO2e assuming all non-renewables derived electricity.

4.5.5. Turning to the best-case scenario, the lower impact of producing the 44 steel foundation WTGs is plotted against comparable annual emissions for CCGT gas and all non-renewables in Figure 4.2. The changes are noticeable, and the Project would instead be expected to achieve payback in between 2.0-2.2 years (and then deliver annual savings for each of the following years of operation).

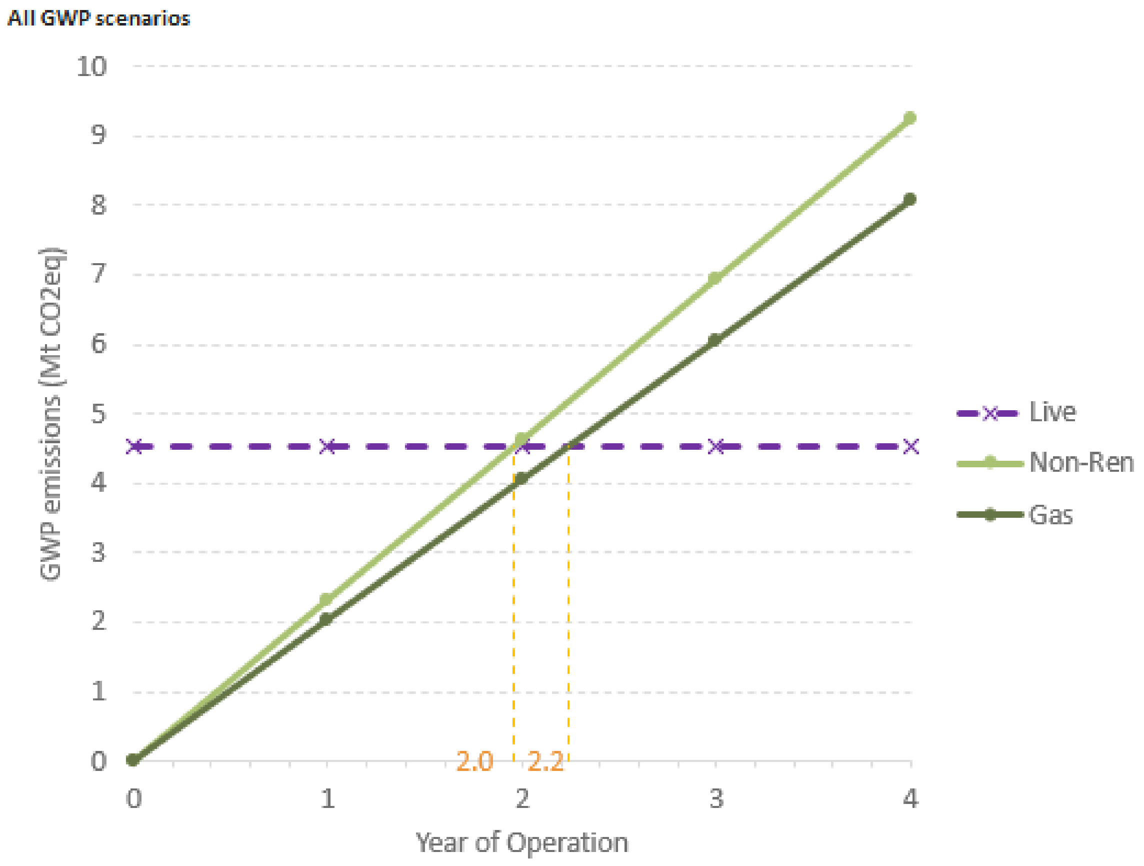

*Figure 4.2 GWP "Pay-back" Analysis for the best-case scenario (Scenario 1 with concrete foundations)*

4.5.6. Operating for 35 years, with a higher annual power generation of 5,500 GWh, the cumulative emissions of the alternative electricity sources would be 70.8 Mt CO2e (CCGT) or 80.8 Mt CO2e (all non-renewables), between 15 and 17 times the lifetime carbon impacts of the Project, depending on the alternative electricity source.

4.5.7. Overall, the Project's best-case scenario is also deemed to have a significant net benefit regarding lifetime emission reduction compared to the project baseline scenarios, with a net benefit of 66.2 Mt CO2e assuming CCGT and 76.3 Mt CO2e assuming all non-renewables derived electricity.

## 4.6. SENSITIVITY TESTING

4.6.1. As demonstrated in Figure 4.1 and Figure 4.2 above, it is good practice to explore how the results might depend on important uncertainties or assumptions in the underlying data. In this instance, the results are quite conclusive that the Project (best and worst-case) is (10-17 times) better than the likely counterfactual electricity alternatives. However, it is still instructive to explore how much the values might change, based on changes in the underlying data. In this section, two further checks are performed below.

## 4.7. ANNUAL ELECTRICITY PRODUCTION

4.7.1. It was stated above in Section 4.4.1 that there is some uncertainty about the amount of electricity that the Project might annually produce, with the initial values used being 4,650 and 5,500 GWh/yr (worst- and best-case scenarios). Underpinning these values is an inherent assumption about the possible load factor of the Project; what if that were unduly optimistic (or pessimistic)?

4.7.2. To explore this, alternative scenarios were proposed, in which the electricity generated might differ from the initial assumption (of 52.9%). Alternative values of 40.58% (from RenewableUK, based on the last five years of generation; Renewable UK, n.d.) and 61.5% (from UK Government estimates for new-build wind farms from 2025-2028; Department for Energy Security & Net Zero, 2023) were selected.

4.7.3. Reducing the assumed Load Factor from 53% to 41% increases the payback time (for the worst-case scenario) to 4.0-4.5 years, so has little effect on the results. To explore a much more extreme possibility, the annual electricity production was halved, to 2,325 GWh/yr. Even under these circumstances, the Project still achieved carbon payback after 6.1-7.0 years of operation.

4.7.4. Comparatively, the abovementioned scenarios of reduced Load Factor and electricity production were also applied to the best-case scenario. Reducing the Load Factor to 41% increases the payback time (for the best-case scenario) to 3.0-3.4 years, so has little effect on the results. A halving of the annual electricity production to 2,700 GWh/yr, would still see the Project achieve carbon payback after 3.9-4.5 years of operation.

4.7.5. Conversely, a higher Load Factor for the Project of 62% for both scenarios was also evaluated. Under these circumstances, the Project would achieve carbon payback in 2.6-3.0 years (for the worst-case scenario) and 2.0-2.2 years (for the best-case scenario).

4.7.6. The Project’s GHG results are seen to be relatively robust to uncertainties around the exact amount of electricity that will be generated across both the best and worst-case scenarios, in each case achieving carbon payback in under seven years of operation.

### CONSTRUCTION BURDENS

4.7.7. As there are some uncertainties about the exact details surrounding the materials to be used for the Project, it was decided to explore how the results would change if the material burdens were double the originally estimated values (as were their manufacturing, transport and installation values). In this scenario, the Project (worst-case scenario) would take 5.9-6.8 years to payback its carbon burden. For the best-case scenario, the Project would take 3.8-4.3 years to payback its carbon burden. Overall, these results demonstrate the strong carbon benefit of the Project.

# 5. SUMMARY

5.1.1. This study has performed an LCA of the Project. The scope considered impacts across the whole life cycle, from the production of the raw materials used to construct the facility, all the way through to the recycling or disposal of those same materials after decommissioning at the end of its lifetime.

5.1.2. The GHG emissions across an assumed 35-year lifetime operation with 67 WTGs and their anchor foundations are estimated to be 6.0 Mt CO2e (worst-case scenario). The Project is expected to produce 4,650 GWh of electricity each year, meaning the carbon intensity of the electricity generated will be about 36.9 g CO2e/kWh.

5.1.3. The GHG emissions across an assumed 35-year lifetime operation with 44 WTGs and concrete based foundation system are estimated to be 4.5 Mt CO2e (best-case scenario). The Project is expected to produce 5,500 GWh of electricity each year, meaning the carbon intensity of the electricity generated will be about 23.7 g CO2e/kWh.

5.1.4. When compared with the alternative of generating the electricity by gas (CCGT) (with a carbon intensity of 371 g CO2e/kWh) or “all non-renewables” (424 g CO2e/kWh), the Project will pay-back the embedded emissions in its construction in two-three years for the best-case scenario, and under four years for the worst-case scenario.

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