DAVIES, A.J. and HASTINGS, A. 2023. Greenhouse gas emissions from decommissioning manmade structures in the marine environment: current trends and implications for the future. *Journal of marine science and engineering* [online], 11(6), article number 1133. Available from: https://doi.org/10.3390/jmse11061133

Greenhouse gas emissions from decommissioning manmade structures in the marine environment: current trends and implications for the future.

DAVIES, A.J. and HASTINGS, A.

2023

Journal of
Marine Science
and Engineering

MDPI

Article

Greenhouse Gas Emissions from Decommissioning Manmade Structures in the Marine Environment; Current Trends and Implications for the Future

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Abstract: The decommissioning of manmade structures in the marine environment causes large volumes of greenhouse gas (GHG) emissions to be released. Current GHG emissions calculation methods for decommissioning offshore oil and gas industry infrastructure leave large sources of GHG emissions unaccounted for. The results presented here show that these consequential decommissioning GHG emissions are underreported by 50%. Until now, no study has looked at the cumulative impact of decommissioning, but this study shows that globally offshore oil and gas infrastructure decommissioning has produced 25 $MtCO_2e$ to date, around 0.5% of annual global GHG emissions. Importantly, this study also shows that due to the growth of the offshore wind industry, increasing numbers of manmade structures will be emplaced in the marine environment, and GHG emissions from decommissioning will increase 200-fold to 5 $GtCO_2e$ by 2067. Crucially, this growth of GHG emissions is not compatible with the Paris Agreement, and new decommissioning methods will be required to meet this challenge.

Keywords: greenhouse gas emissions; decommissioning; offshore energy industry; oil and gas; renewables

Citation: Davies, A.J.; Hastings, A. Greenhouse Gas Emissions from Decommissioning Manmade Structures in the Marine Environment; Current Trends and Implications for the Future. *J. Mar. Sci. Eng.* **2023**, *11*, 1133. https://doi.org/10.3390/jmse11061133

Academic Editor: Weidong Zhai

Received: 9 May 2023
Revised: 26 May 2023
Accepted: 26 May 2023
Published: 28 May 2023

1. Introduction

Decades of industrial activity have taken place in the marine environment, including hydrocarbon (HC) exploration and production by the oil & gas industry (OGI) and, more recently, the offshore wind industry (OWI). The manmade structures required for these endeavors include drilling and production rigs, steel and composite wind turbines, pipeline and cables, heavy cement and steel structures, debris and waste on the seabed, large topsides, heavy lift cranes, helicopter landing pads, industrial equipment, accommodation blocks, power generation infrastructure, safety vessels, and many other components that make these huge and highly complex industrial facilities, some of which are illustrated in Figure 1.

At the end of its useful life, the infrastructure must be decommissioned. When and how this is performed is very much dependent on the local laws and policies but is, in essence, a vast engineering challenge in an extreme environment that requires a substantial input of energy, usually in the form of fossil fuels and, consequently, large volumes of GHG emissions are released.

OGI decommissioning programs can vary in size and complexity and range from the decommissioning of a single structure to the decommissioning of entire fields. The specific equipment and infrastructure required depend on what is needed for the exploration, production and transport of hydrocarbons (HCs) and are determined by a vast array of variables, including the type of HC present, production volume, water depth, geological location, currents, seasonal and short-term weather patterns, subsea structure, and seafloor structure. OGI infrastructure is often unique, built specifically for a particular field, use or operation, making decommissioning a complex process. The OWI requires around six times more infrastructure than the OGI for the same amount of power output [1], but a proportion of this may be repeated components such as multiple wind turbines all built to the same design, and this may reduce the complexity of the decommissioning process.

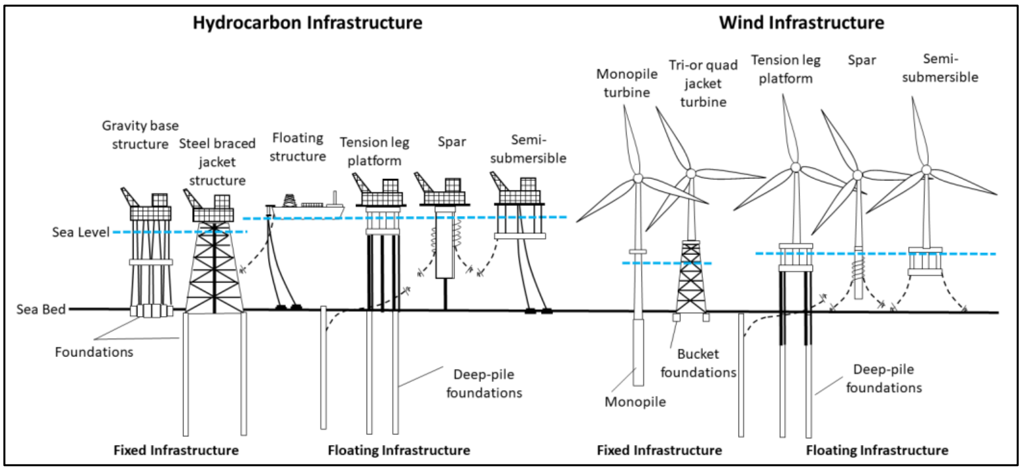

Figure 1. Some examples of the infrastructure required by the oil & gas industry (OGI) in the exploration & production of hydrocarbons and the offshore wind industry (OWI) to produce electricity using offshore wind farms (OWF). Adapted with permission from [1]. 2022, Elsevier.

Decisions regarding the fate of the infrastructure at the end of its working life are limited by factors determined by the local governing body and can range from a 'clear seabed' policy, where it is a legal requirement that all structures are completely removed, to policies that allow the reuse of structures such as the rig-to-reef programs in the US. Most of the countries that make up the Northeast Atlantic Region (NAR) have signed the OSPAR 98/3 agreement, which aims to prevent the dumping of waste at sea and requires that all structures, debris and/or waste from OGI activity are fully removed [2].

How the consequential GHG emissions from decommissioning are calculated and reported is also determined by the local governing body. In the NAR, the Institute of Petroleum (IOP)'s 2000 guidelines [3] are used to calculate the GHG emissions prior to decommissioning taking place. Previous work [4] showed that these guidelines are considerably outdated in terms of both methods and data collection, leaving large sources of GHG emissions unaccounted for and should not be relied upon for accurate GHG emission accounting.

In countries with a carbon tax, such as Norway, a decommissioning close-out report (COR) is a legal requirement. The COR itemizes any differences between calculated pre-decommissioning reported GHG emissions and the actual GHG emissions produced, calculated from the decommissioning operations data. This includes any changes to fuel use, which are hard to predict due to the huge number of variables that can impact fuel consumption, including wind direction and sea state [4].

Decommissioning GHG emission sources include both offshore and onshore operations, as well as transport and shipping of materials to disposal/recycling centers, a source that is commonly excluded from GHG calculations; in fact, there are no expectations in the IOP and therefore, the NAR that any onshore or shipping GHG emissions sources are included at all.

There are currently no models that accurately quantify GHG emissions from decommissioning, nor is there a clear understanding of how these emissions fit into the global context of cumulative global GHG emissions. Importantly, there are also no future projections of GHG emissions due to decommissioning, including no consideration for the future growth of offshore wind and the potential impact this will have on future decommissioning

GHG emissions. Considering the energy transition and the growth of offshore renewables, especially offshore wind farms (OWF), large numbers of new manmade structures will be required in the marine environment over the coming decades [5], the direct result of which will be significant and growing GHG emissions due to decommissioning; a challenge which has so far not been recognized nor planned for.

This study aims to address these considerable gaps in the knowledge and begins with an analysis of GHG emissions from OGI decommissioning operations in the UK North Sea, then places these in the context of global cumulative GHG emissions due to OGI decommissioning and finally, a prediction of future GHG emissions from OGI and OWF decommissioning programs up to 2067.

2. Materials and Methods

2.1. Methods

There were two main stages to the study. The first stage was to quantify GHG emissions due to OGI decommissioning and took a two-step approach; firstly, pre-decommissioning GHG emissions data was mined from publicly available decommissioning program reports. GHG emission data was found for 44 decommissioning programs, and this was then combined to find the cumulative GHG emissions from all 44 programs. The original pre-decommissioning data was then compared to post-decommissioning emission accounts, and an average emissions gap was determined. This average emissions gap was applied to all other estimated pre-decommissioning emissions to reflect a more accurate model of the post-decommissioning emission costs. The next step was to apply the Value Retention Model (VRM) as applied to the decommissioning industry [4]. This takes a life-cycle assessment approach to determine the GHG emission consequences of various end-of-life options, including recycling and disposal (Figure 2). Figure 3 describes how the model can be applied specifically to four end-of-life scenarios and the embedded emissions retained or lost as a consequence of each. Using the VRM method for steel Material Value (MV) (the value created and embedded when the material is manufactured) is 1.85 tCO_2e/tsteel and Product Value (PV) (the value created and embedded when the product is manufactured from the materials) is 1.59 tCO_2e/t steel. Therefore, materials reused or refurbished would retain both the MV and the PV (Figure 3a,b), recycling would lose the PV but retain the MV (PV loss = 1.59 tCO_2e/tsteel) (Figure 3c), and material sent for disposal would lose both the MV and PV (MV + PV loss = 3.44 tCO_2e/tsteel) (Figure 3d). Various materials are decommissioned during operations, such as plastics, metals and wood, and require end-of-life decisions to be made. However, due to the lack of published material inventories in the GHG emissions calculations and because steel is by far the most decommissioned material to be dealt with [4], this model uses steel as the proxy input material.

The next stage was to place these GHG emissions into context in terms of global cumulative emissions. Due to a lack of context and timescales in the data collected, it was not possible to predict GHG emissions in a wider context from this data, and therefore, an alternative method was required to model annual GHG emissions and cumulative future trends. Cost data for decommissioning projects was much more accessible, and this was used to find a relationship between cost and GHG emissions produced. The only GHG emissions figures available from previous work are that of [4] who established that to decommission a 50,000 t steel structure, 110,000 tCO_2e of GHG emissions would be produced. This was the basis for the cost:emissions calculations (refer to Table 1), the methods for which are described below.

1. The total estimate of costs to decommission everything in the North Sea was found (~£45 b over 20 years [6]).
2. Then a percentage of this total was allocated to steel jackets, which make up 20% of the total [7].
3. The total number of jackets was found, then the GHG emissions figure from [4] was applied. This represents 20% of the total infrastructure, so it was straightforward to determine the total GHG emissions.

4. The total GHG emissions figure of 176 $MtCO_2e$ was divided by costs (~£45 b) to find the amount of GHG emissions figure per billion £ (3.83 $MtCO_2e$/£b).
5. The next stage was to find the cost of global decommissioning and apply the GHG figure/£b as determined in step 4.
6. Future decommissioning trends were included, and a future GHG emission trend was determined.

The final stage of the project was to look at future global decommissioning trends and how this impacts cumulative GHG emissions. Interestingly one consequence of the transition away from fossil fuels towards renewably sourced energy is a huge upward surge in manmade structures in the marine environment [1,5,8,9], which will lead to a huge upward surge of decommissioning activity once this infrastructure is at the end-of-life; 25 years after installation.

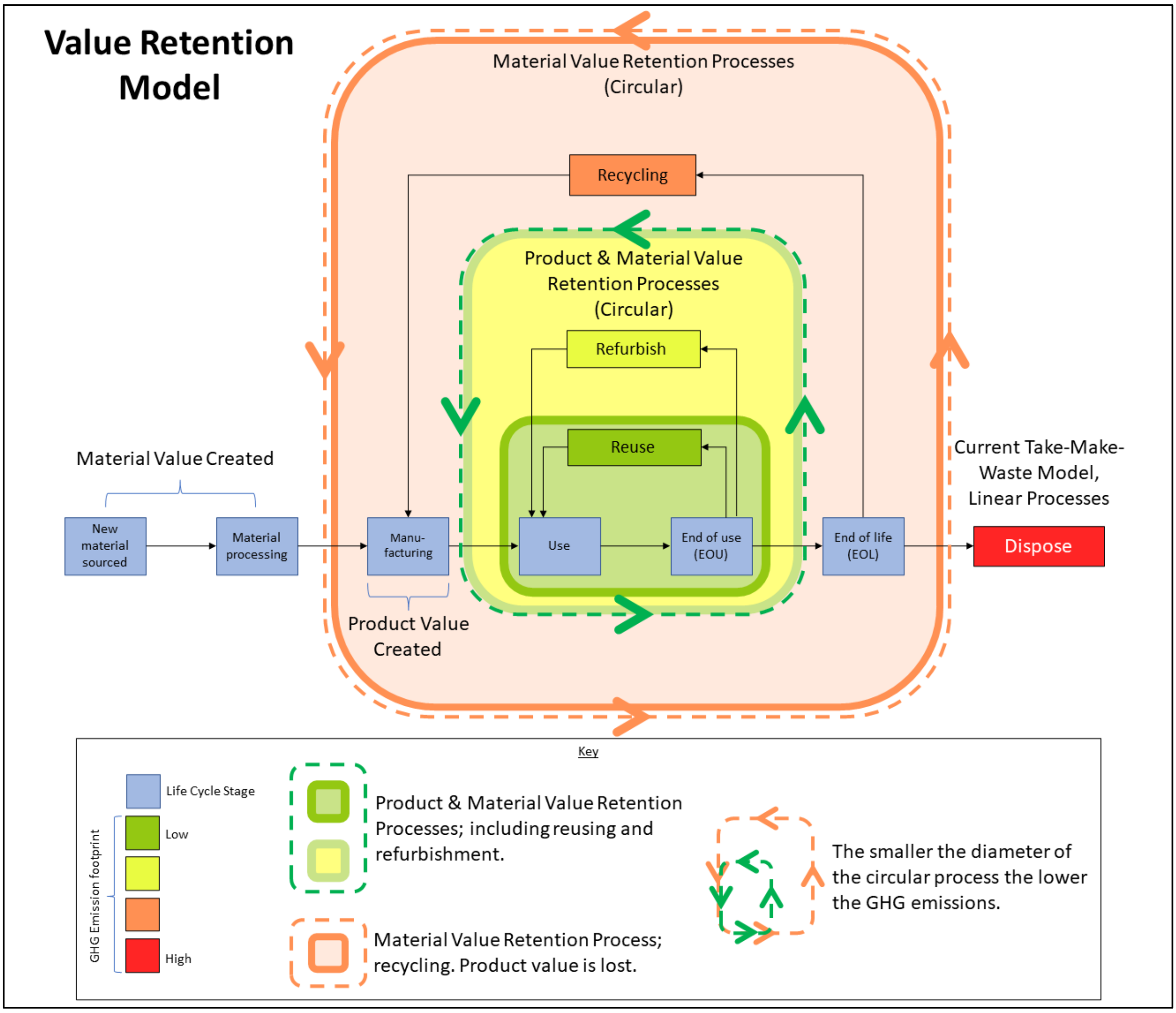

Figure 2. The Value Retention Model (VRM) is applied to the decommissioning industry. The VRM uses circular approaches to retain the embedded value or carbon within the infrastructures to be decommissioned. Within the product (orange) and material (green and yellow) value retention processes, the smaller the diameter of the circular process, the smaller the GHG emissions will be. Adapted from [4].

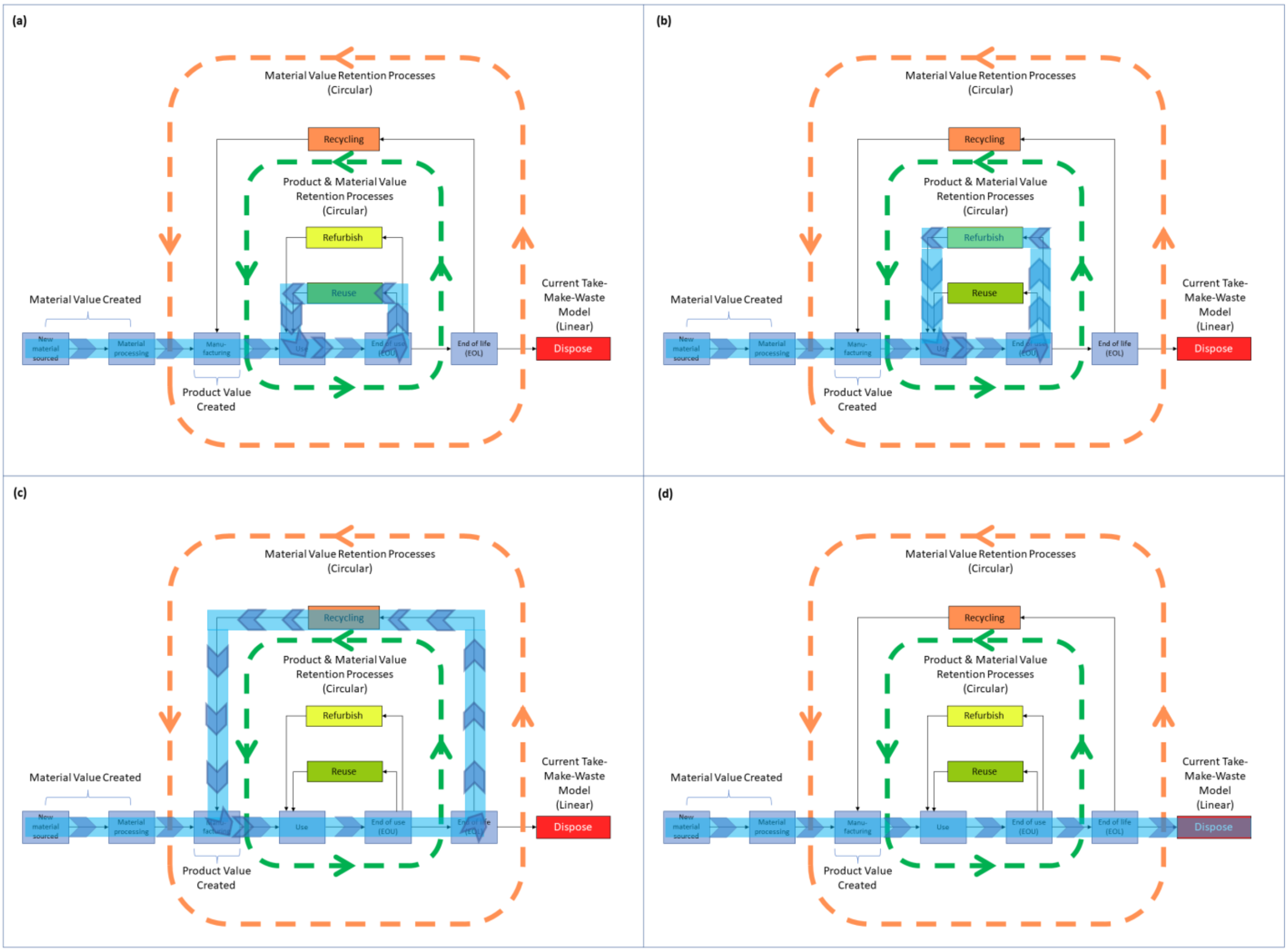

Figure 3. Decommissioning pathways through the VRM illustrate the practical use of the model to quantify GHG emissions from material end-of-life scenarios. Panels (**a**–**d**) illustrate the different pathways for material end-of-life decisions, reuse, refurbishment, recycling, and disposal. Adapted from [4].

To find a cost:emissions ratio for offshore wind (refer to Table 2), the cost to decommission was determined per GW, and a GHG emissions figure was applied to future trends [10–12], as per the following steps:

1. Decommissioning cost was established to be £1.333 b/GW [8].
2. The GHG emissions per GW were determined to be 6.27 $MtCO_2e$/GW [10].
3. As the above figure does not include onshore activity such as dismantling, or onward transport, 20% was applied to the figure in step 2; 7.52 $MtCO_2e$/GW
4. Current wind capacity was then found; 55,678 MW for 2021 [13].
5. The total GHG emissions from decommissioning were then found by multiplying capacity by GHG emissions; GHG emissions per GW x Capacity (GW) = Total GHG Emissions
6. The next stage was to work out future decommissioning trends. Growth rates are predicted at 18.6% [11] for the years 2019–2024, with a smaller growth rate of 8.2% thereafter [10]. These figures were used to predict future emissions from decommissioning activity.

2.2. Materials

This study mined publicly available GHG emission data from OGI decommissioning programs in the UK North Sea as submitted to the regulator as part of the decommissioning approval process. Forty-four decommissioning programs contained GHG emissions data presented in various formats (Table 3). The IOP methodology was presumed to have been used in all cases as per UK governmental guidance. However, few reports specifically stated this. Different OGI operators present the data in different formats and in different reports or as part of appendices in different reports. Some data was found in the Environmental Impact Assessments or Environmental Statements submitted to OPRED for approval, but not all of these reports were available. Furthermore, data was also unavailable for a number of reasons, including a backlog in digitizing paper reports caused by the COVID pandemic and the fact that GHG emission reporting was not a legal requirement before 2001. Some operators itemize the reported emissions into basic categories, such as materials sent for disposal and recycling or vessel use, but some do not itemize at all. Some reports refer to more detailed data, but in these cases, the data was an appendix of the main report, and the appendices were not available. A few operators included items such as helicopter fuel use, and there is one example where the operator included calculations for P&A; both examples are not required to be included by the regulator. The second set of data was GHG emissions, as reported in the COR submitted to OPRED/BEIS after the decommissioning program was complete. Only two CORs contained this data, both from an OGI operator for decommissioning programs that straddled Norwegian and UK waters, and this data was a requirement for the Norwegian regulator.

Data was analyzed as both individual decommissioning program emissions and as a cumulative of all 44 decommissioning program emissions, as it is the cumulative effect of GHG emissions that causes climate change. Without exception, all the collected GHG emission data was in CO_2e and was not itemized by other GHGs, for example, methane.

Tables 1 and 2 show the data used within this study for the OGI (Table 1) and OWI (Table 2).

Table 1. Data used for analysis for OGI decommissioning current and future trends.

Offshore Hydrocarbon Decommissioning			
	Data	**Unit**	**Reference**
UKNS number of steel structures	320		[6]
Proportion of above to rest of infrastructure	20	%	
GHG emission per steel jacket	110,000	tCO_2e	[4]
GHG to decom all steel jackets	35.2	$MtCO_2e$	
Total GHG emissions	176	$MtCO_2e$	
Total Cost	45	£b	[7]
GHG Emission per cost	3.91	$MtCO_2e$/£b	
Onshore and shipping est	20	%	
Total GHG Emission per cost	4.69	$MtCO_2e$/£b	
Global decom cost to 2024	42	£b	[14]
Global decom GHG emissions to 2024	197.12	$MtCO_2e$/£b	
Rate of Decom growth	4.9	%	[14]

Table 2. Data used for the analysis of offshore wind decommissioning current and future trends.

Offshore Wind Decommissioning			
Input variables	**Data**	**Unit**	**Reference**
Decommissioning cost	1.333	£b/GW	[15]
GHG emissions per GW	6.27	$MtCO_2e$	[10]
Onshore and shipping estimate	20	%	
Decommissioning emissions	7.52	$MtCO_2e$/GW	
Wind capacity 2021	55,678	MW	[13]
Growth rate from previous year	62	%	[11]
Growth rate 2019–2024	18.6	%	[11]
Growth rate from 2024	8.20	%	[10]

Table 3. GHG emission data extracted from 44 OGI decommissioning programs.

GHG Emissions from North Sea OGI Decommissioning Programs				
Name	**Operator**	**GHG Emissions (tCO_2e)**	**No. On Graph**	**Reference**
North Cormorant Topsides	TAQA	17,018	1	[16]
Tern Topsides	TAQA	21,667	2	[17]
PL301 Heimdal to Brae Alpha Condensate Pipeline	Equinor	9,487	3	[18]
Gaupe	Shell	3,506	4	[19]
Buchan & Hannay	Repsol Sinopec	11,232	5	[20]
Ensign	Spirit Energy	6,344	6	[21]
Windermere	INEOS	23,574	7	[22]
East Brae and Braemar	Marathon Oil	32,191	8	[23]
Brae Alpha	Marathon Oil	92,000	9	[24]
Brent	Shell	63,045	10	[25]
Atlantic & Cromarty	Hess Ltd. & BG group	14,000	11	[26]
Anglia	Ithaca Energy	12,600	12	[27]
Alma & Galica	EnQuest	11,952	13	[28]
Brynhild	Lunin	3,998	14	[29]
Cavendish	Ineos	3,686	15	[30]
Caister	Chrysaor	5,374	16	[31]
Cormorant Alpha Derrick	TAQA	1,639	17	[32]
South Morecambe DP3-DP4	Spirit Energy	56,876	18	[33]
Eider Topsides	TAQA	9,411	19	[34]
LOGGS Area	Chrysaor	19,019	20	[35]
Macculloch	ConocoPhillips	11,262	21	[36]
Ketch and Schooner	DNO	21,018	22	[37]
Juliet	Neptune Energy	9,388	23	[38]
Viking VDP1 and Loggs LDP1	ConocoPhillips	91,623	24	[39]
Merlin	Fairfield	8,619	25	[40]
Ospey	Fairfield	20,579	26	[41]
Dunlin	Fairfield	9,704	27	[42]
Markham	Spirit Energy	16,280	28	[43]
Rev	Repsol	2,421	29	[44]
Saturn (Annabel) & Audrey Fields	Spirit Energy	39,227	30	[45]
Ann & Alison Fields	Spirit Energy	21,250	31	[46]
Ann A4	Centrica	745	32	[47]
Etrick & Blackbird	Nexen	68,263	33	[48]
Athena Field	Ithaca Energy	20,717	34	[49]
Janice, James, Affleck Fields	Maersk Oil	101,507	35	[50]
Tyne	Perenco	20,143	36	[51]
Guinevee	Perenco	20,668	37	[52]
Leadon	Maersk Oil	7,740	38	[53]
Curlew	Shell	64,200	39	[54]
Jacky	Ithaca Energy	15,177	40	[55]
Bains	Spirit Energy	1,673	41	[56]
VDP2	ConocoPhillips	258,549	42	[57]
VDP3	ConocoPhillips	20,980	43	[57]
Rubie Renee	Endeavor	25,627	44	[58]
Cumulative Emissions (tCO_2e)		1,295,978		

3. Results

3.1. Reported Pre-Decommissioning GHG Emissions

Figure 4 illustrates the GHG emissions for 44 decommissioning programs as reported to OPRED/BEIS between 2005–2020 by OGI operators. Individual programs vary greatly in both scale and complexity, and as such, a large range of data is observed; for example, the decommissioning of a single wellhead protector has the lowest estimated GHG emissions at 745 tCO_2e. The largest volume of GHG emissions was 258,549 tCO_2e from a decommissioning program that consisted of a number of operations such as the removal of large steel jackets, topsides, subsea structures and pipelines and required the use of specialized equipment such as heavy lift vessels that use large volumes of fossil fuels.

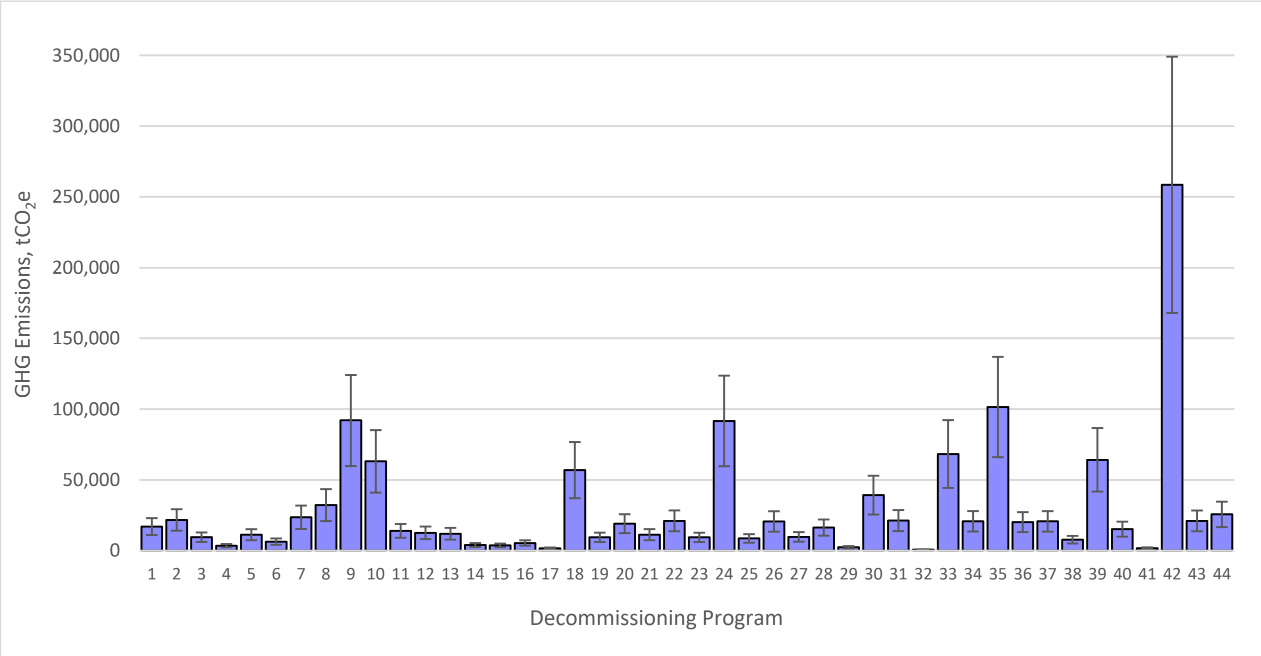

Figure 4. GHG emissions from individual decommissioning programs in the UK North Sea, numbered 1–44. This is publicly available data mined by the authors from decommissioning reports from multiple OGI operators. The corresponding data and references for the data are available in Table 3. Error bars are IOP methodology errors of 30–35% [3].

Cumulative GHG emissions were calculated from the 44-decommissioning program, illustrated in Figure 5 and a total of 1.3 $MtCO_2e$.

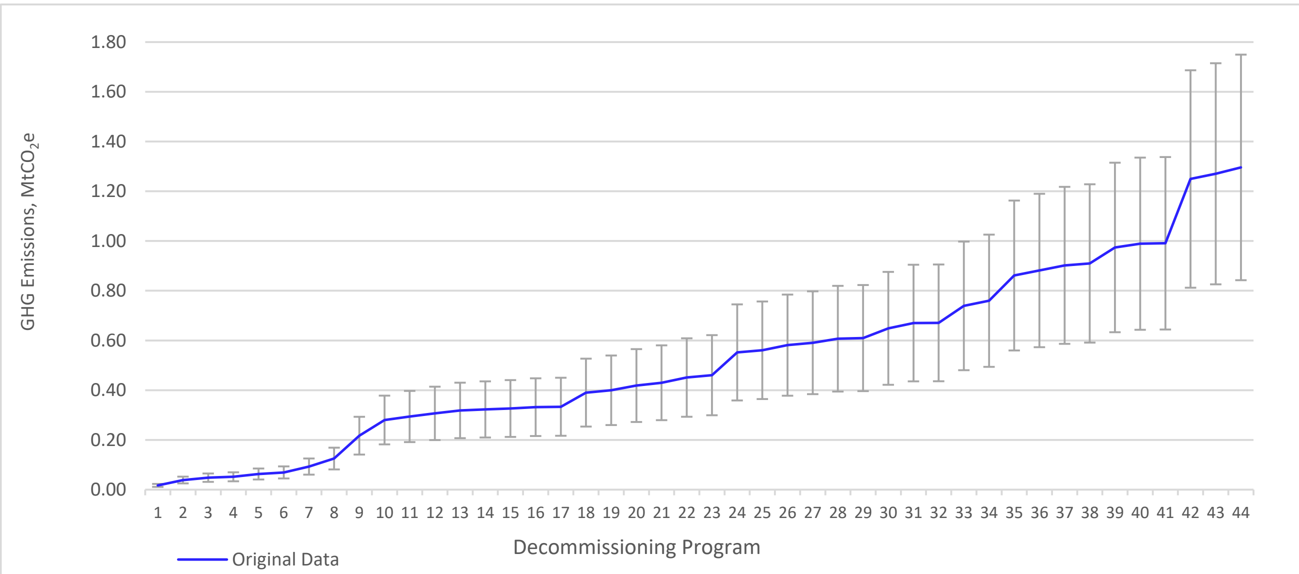

Figure 5. Cumulative GHG emissions from the data in Figure 4. IOP errors of 30–35% are represented by the grey vertical lines and are also cumulative. This represents a proportion of decommissioning programs undertaken or planned in the UK North Sea.

3.2. Close-Out Report GHG Emissions

To investigate the accuracy of the pre-decommissioning GHG emissions reporting, a comparison was made between pre-decommissioning GHG emission estimates and post-decommissioning GHG emissions calculated using the actual operations data. Only two projects were found that itemized this data in the COR, the Viking VDP1 decommissioning program and the LOGGS LDP1 decommissioning program, both from the same operator [59].

Pre-decommissioning data from VDP1 estimated emissions to be 53,026 tCO_2e in total, with fuel use for vessels and power making up 77% of this. Program LDP1 pre-decommissioning estimated emissions were 39,066 tCO_2e, 68% of which was for fuel use. Both the programs had a higher actual fuel use than predicted by 50%, increasing the total emissions to 73,479 tCO_2e and 52,280 tCO_2e, respectively, as described in Figure 6. The 50% increase in fuel use translates to an increase in total GHG emissions of 36.2%. Figure 7 illustrates the impact on cumulative emissions when this modeled increase is applied to all programs and shows that the total cumulative GHG emissions are now 1.77 $MtCO_2e$, up from 1.3 $MtCO_2e$.

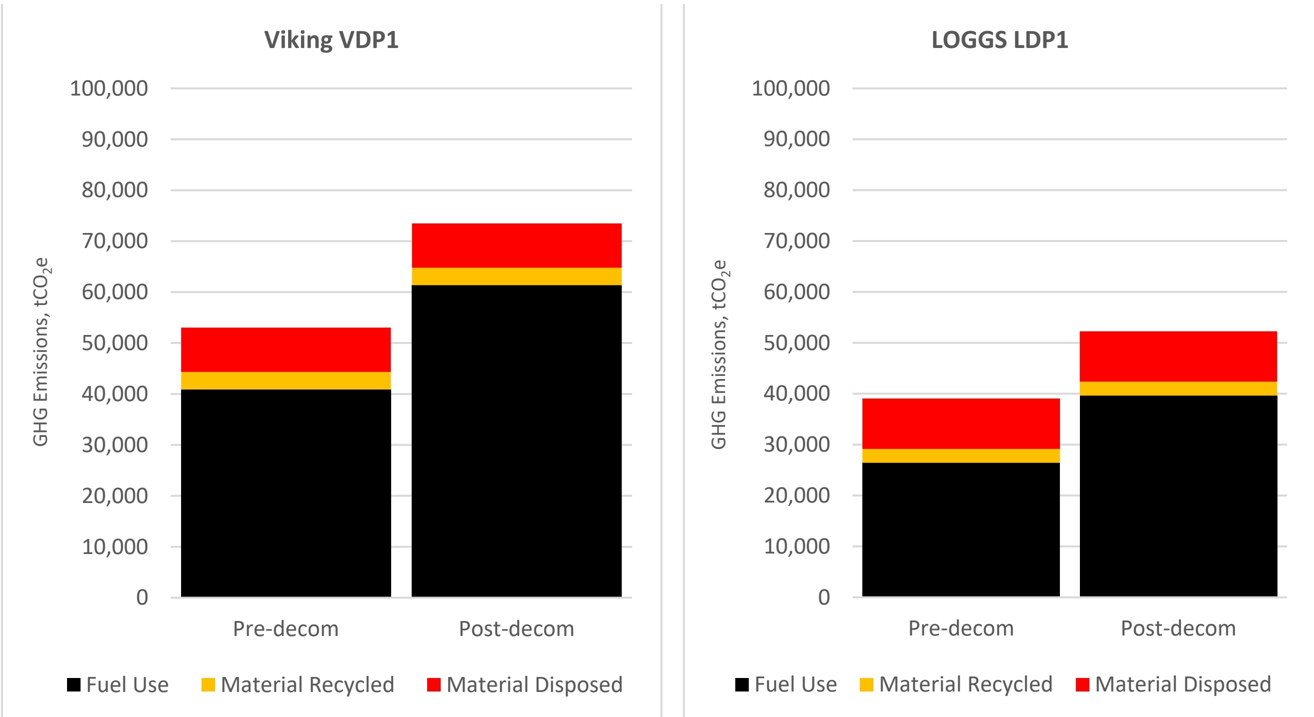

Figure 6. GHG emissions for two decommissioning programs; Viking VDP1 and LOGGS LDP1. Pre-decommissioning estimates of GHG emissions from fuel use (black), materials sent for recycling (orange) and materials disposed of (red). Data from [39,59].

3.3. Value Retention Model GHG Emissions

The material inventory was unchanged between pre-and post-decommissioning, meaning that the volumes and weights of materials decommissioned were as expected pre-decommissioning. VDP1 had 8696 t of materials to dispose of and 3425 t of material sent for recycling. Using the MVM method and data from [4] where Material Value (MV) is 1.85 tCO_2e/t steel and Product Value (PV) is 1.59 tCO_2e/t steel, the material to be disposed of would lose both the MV and PV, loss = MV + PV = 29,914 tCO_2e. The material sent for recycling would lose the PV but retain the MV (loss = PV = 5446 tCO_2e). Figures 8 and 9 illustrates the impact of this change on the total cumulative GHG emissions, now at 2.59 $MtCO_2e$, double the original cumulative value.

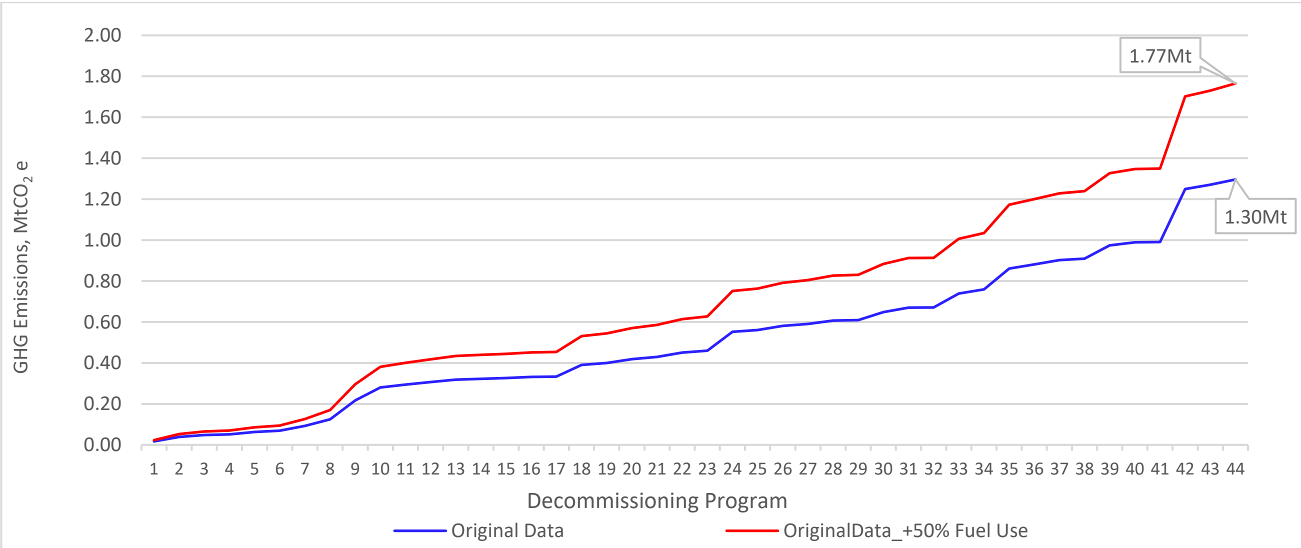

Figure 7. Cumulative GHG emissions. The blue line shows the original data as per Figure 4, and the red line illustrates that the impact of fuel use is 50% higher than estimated in the pre-decommissioning reports.

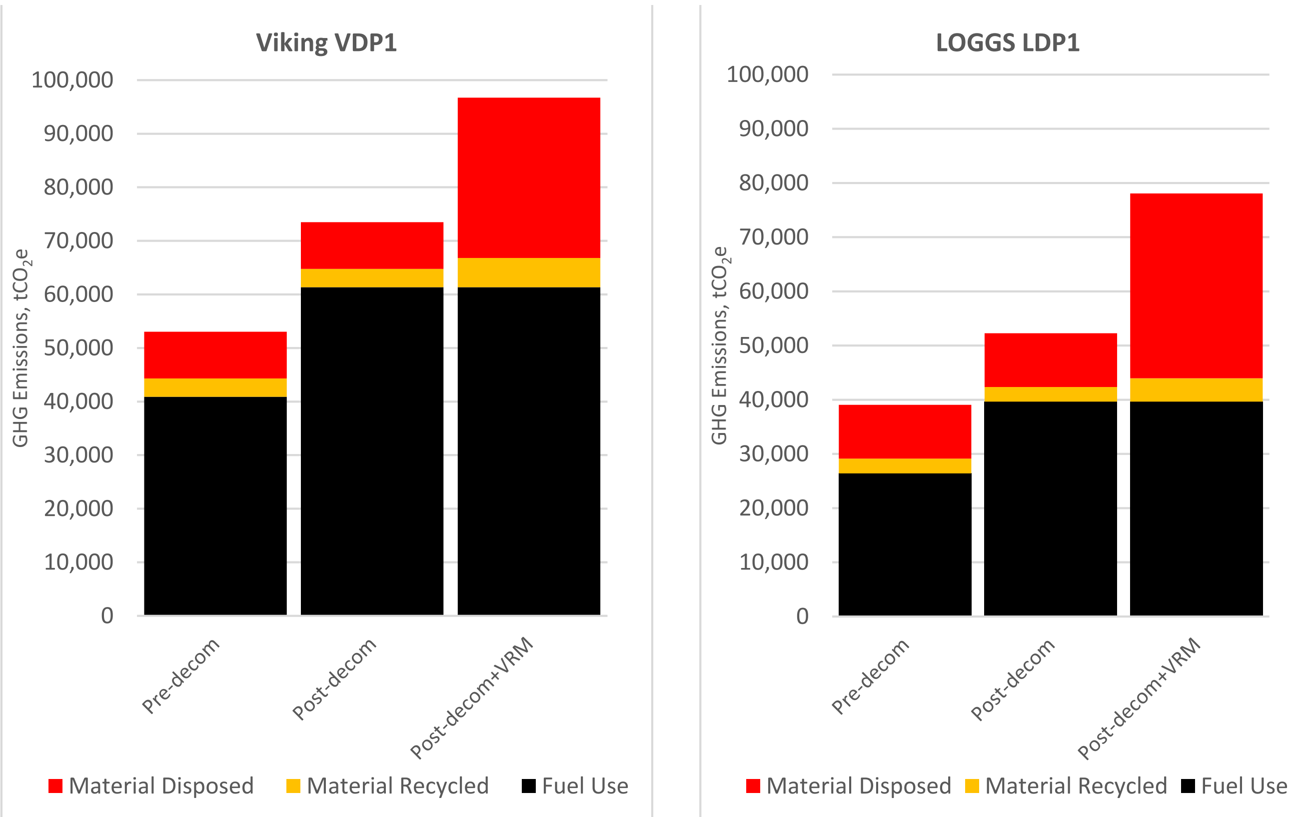

Figure 8. Shows the impact on the total GHG emissions for VDP1 and LDP1 when the VRM is applied. VDP1's total GHG emissions are 96,717 tCO_2e, and LDP1's total GHG emissions are 78,081 tCO_2e. The average difference between pre- and post-VRM applications is 191%, as there are very few other material inventories available; this difference has been applied to the cumulative data.

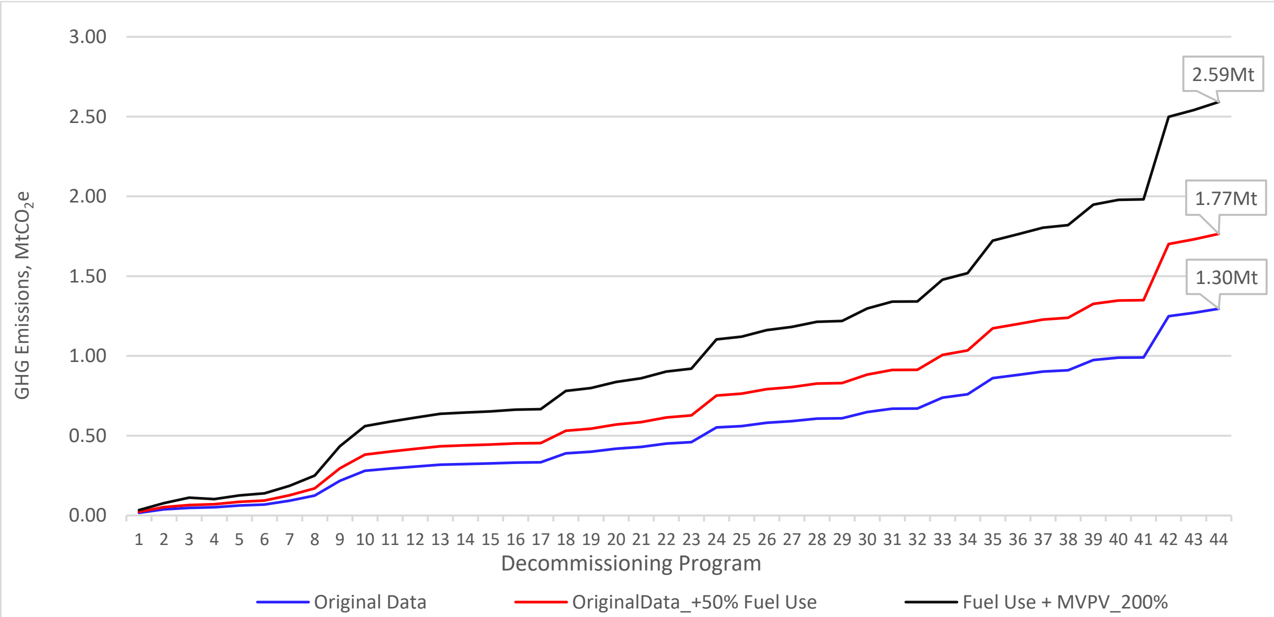

Figure 9. Comparison of original data (pre-decommissioning), the impact of a 50% increase in fuel use (compared to pre-decom estimates) during operations and the impact of applying the Value Retention Model as described in [4].

3.4. Decarbonization

The Paris Agreement and the legislative drive to Net Zero will require that the decommissioning industry put into place GHG reduction strategies. Although local policy will impact the speed at which Net Zero must be achieved, the entire global industry will be impacted. Figure 10 shows the GHG emissions reductions required based on today's reported data of 1.30 $MtCO_2e$ and the legally binding reduction target in the UK of 78% by 2035. This is a reduction of over 1 $MtCO_2e$. Figure 11 shows the adjusted decommissioning GHG emissions figure of 2.59 $MtCO_2e$ with the same reduction target of 78% by 2035 (0.57 $MtCO_2e$), which means GHG emissions must be reduced by more than 2 $MtCO_2e$.

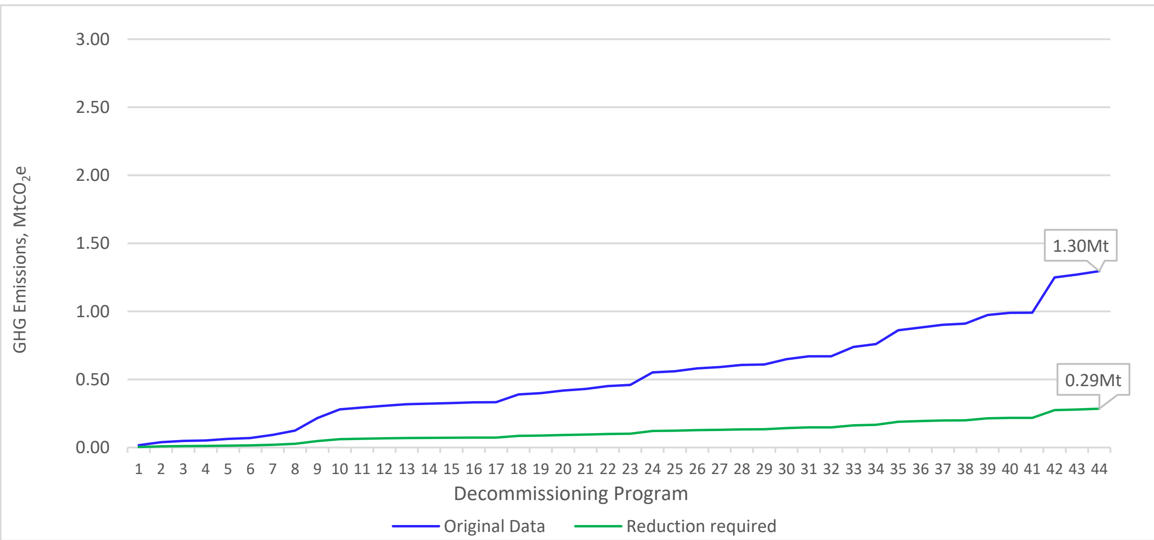

Figure 10. Current estimates of cumulative GHG emissions for the 44 decommissioning programs using current calculation methods (blue line) requires that 1 $MtCO_2e$ of GHG emissions are not released or are saved (green line) as UK governmental decarbonization legislation requires a 78% reduction in all GHG emissions by 2035.

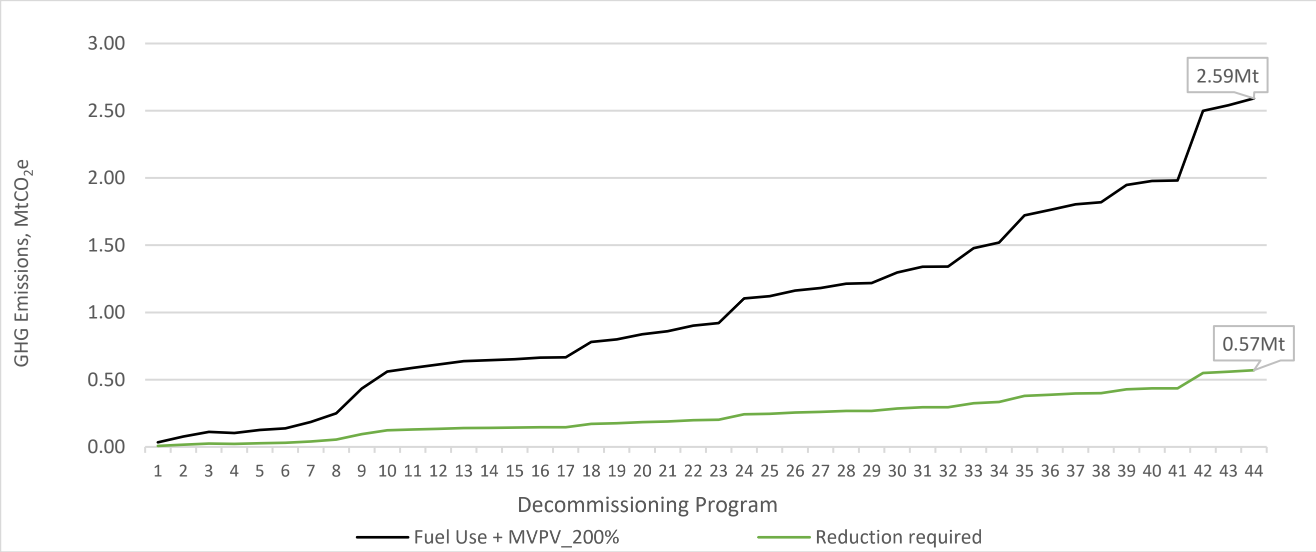

Figure 11. Modeled GHG emissions from this study (black line) and maximum permitted GHG emissions in 2035 with the 78% mandated decrease in emissions for the same 44 decommissioning programs. This represents over 2 $MtCO_2e$ of 'savings' required to achieve UK Net Zero emission goals.

This shows how important a complete picture and account of all GHG emissions is and why it is key to quantify the reductions necessary.

Figures 10 and 11 illustrate why having a holistic, accurate account of all sources of GHG emissions (the baseline) are critical in developing a quantified GHG emissions reduction strategy, as the consequences of not doing this will mean reduction targets will be missed.

3.5. Global Decommissioning Future Trends

The above results are difficult to place into context in terms of the amount of decommissioning activity per annum for the UK or globally due to a lack of transparency and data. However, by using a cost:emissions ratio, we can predict future trends as cost data are much more widely available. Figure 12 illustrates the relationship between cost and emissions, and by this, we can predict that around 25 $MtCO_2e$ of cumulative emissions will be produced from decommissioning by 2022. This has been modeled to increase to around 38 $MtCO_2e$ by the year 2030.

Future decommissioning will include not only OGI infrastructure but also renewable wind infrastructure, Figure 13 illustrates the cumulative capacity reaching almost 700 GW by 2043. This represents a significant increase in the number of manmade objects in the marine environment and will, in time, be reflected in a massive increase in decommissioning activity, assuming policy remains to have a clear seabed. Figure 14 illustrates GHG emissions from decommissioning of the wind turbine infrastructure and shows that with increasing cumulative capacity, cumulative GHG emissions from decommissioning will also increase.

As renewable infrastructure has been designed with a 25-year life span, decommissioning will occur 25 years after installation at the end-of-useful life, but the results show that by 2050 (at which time we should have reached Net Zero), 1 $GtCO_2e$ of GHG emissions could have been released from OWI decommissioning alone. This cumulative figure will continue to grow as wind capacity grows, reaching more than 5 $GtCO_2e$ by 2067 (Figure 14).

3.6. Emissions Risk Matrix

The data and analysis from two decommissioning programs are presented in Figure 8, and an interesting observation is that there are only three variables that are statistically relevant; fuel use, materials sent for disposal and materials sent for recycling because these variables are responsible for the vast majority of emissions produced. By grouping the variables relating to end-of-life options and the VRM model, just two variables remain, meaning that the relationship between them and total GHG emissions can be investigated. When plotted against each other on a graph, we can visualize the data in terms of GHG emissions, as illustrated in Figure 15. Furthermore, the data can now be used to make predictions about GHG emissions because of various decommissioning options, even with very limited data availability.

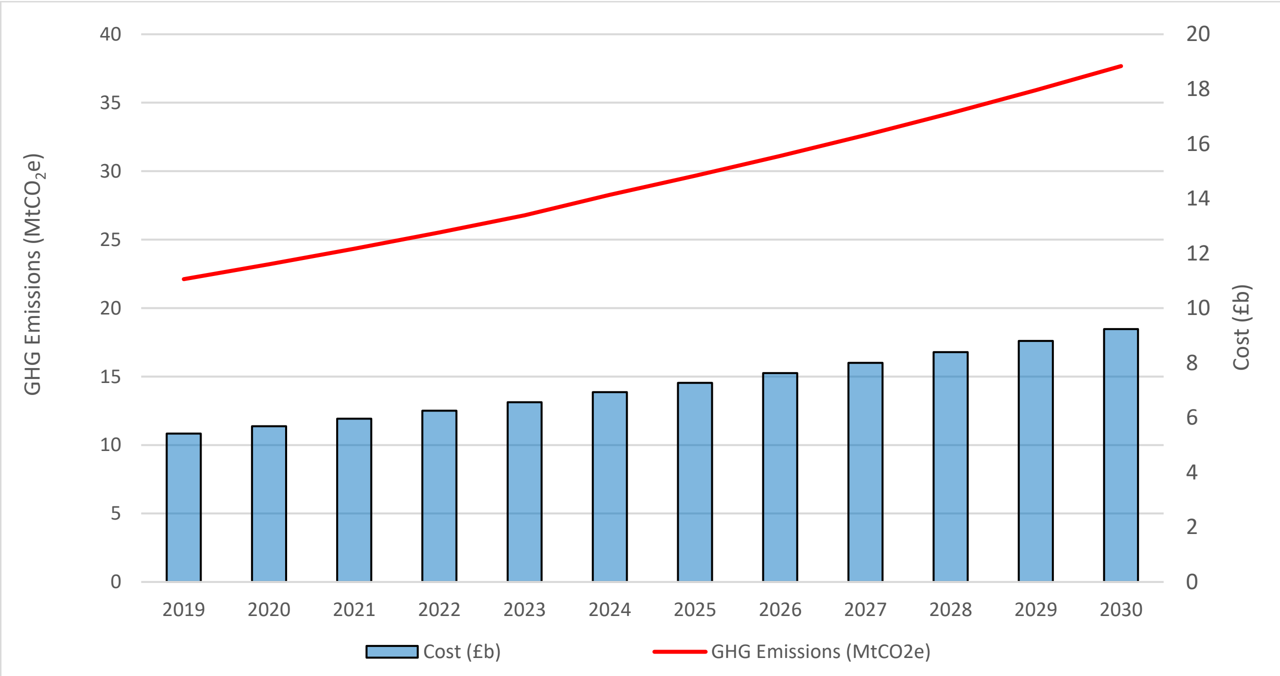

Figure 12. Predicted GHG emissions and cost for global OGI decommissioning. (Data sources: [6–8]).

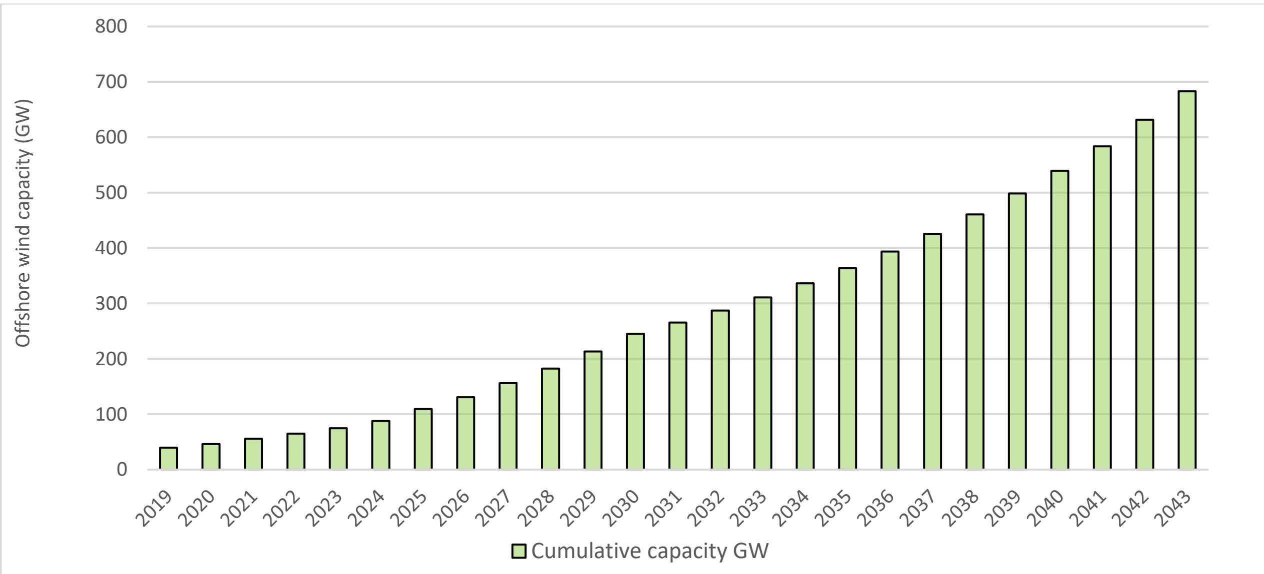

Figure 13. The predicted global cumulative capacity of offshore wind. Data sources: [10,11].

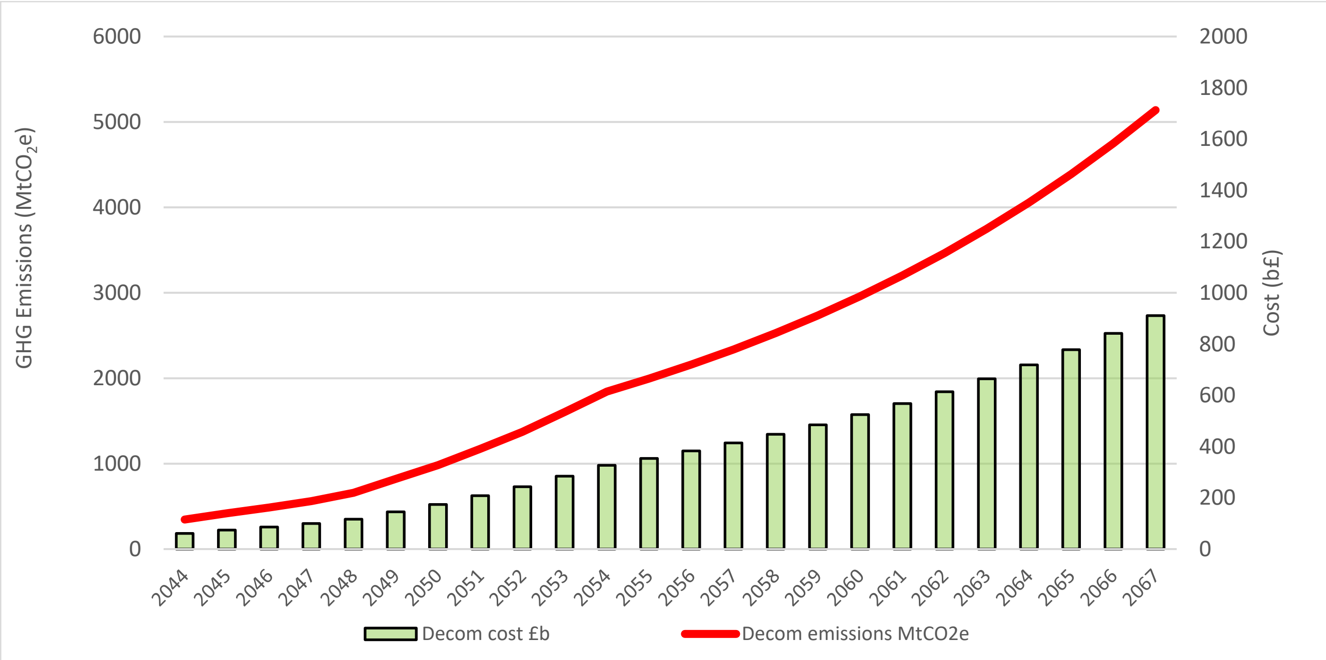

Figure 14. Future global offshore wind decommissioning predictions cost and GHG emissions. Data source: [6,11].

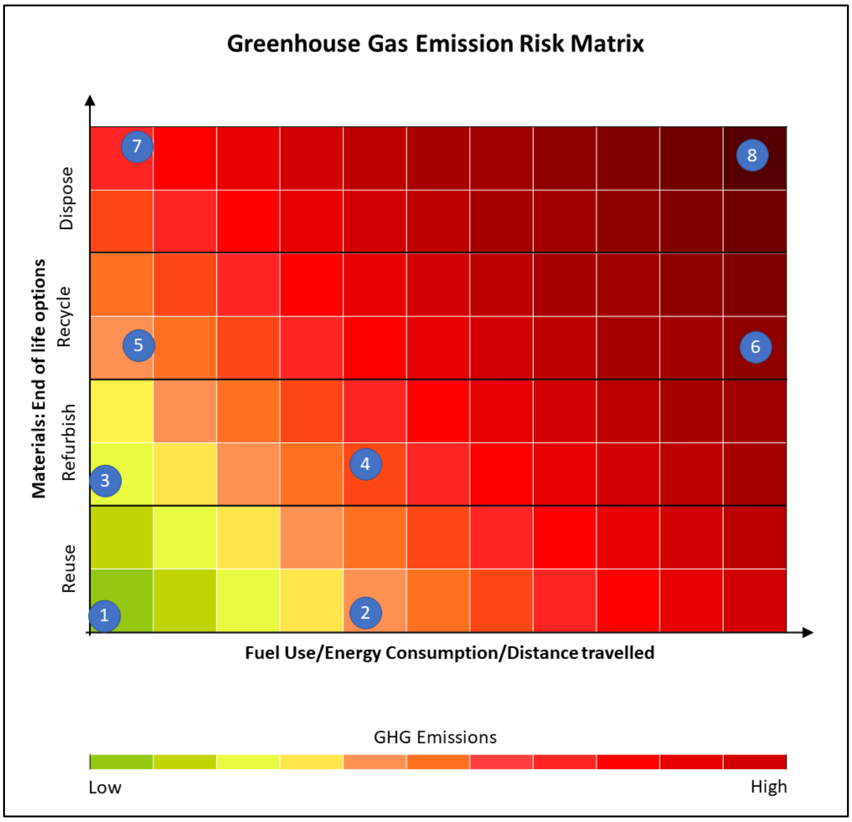

Figure 15. GHG emission risk matrix with the various end-of-life options available for the example of decommissioning a single 50,000 t steel jacket. The numbers are the end-of-life options as follows: 1. Leave in situ for reuse as a reef; 2. Move to a different location for reuse as a reef; 3. Refurbish, in situ, for alternative use such as renewables; 4. Refurbished but moved location; 5. Recycle in the UK; 6. Recycle abroad; 7. Dispose in the UK; 8. Dispose abroad.

In the absence of detailed quantitative GHG emissions figures, the GHG Emission Risk Matrix (GHGERM) (Figure 15) allows various decommissioning decisions or options to be analyzed in terms of the risk of releasing GHG emissions and allows these to be quickly compared to one another. It uses the principles of the circular economy and the waste hierarchy to develop zero waste strategies from material end-of-life decisions as discussed in [4] and plots these values against fuel use, the biggest contributor to GHG emissions from decommissioning.

The example in Figure 15 illustrates the process of taking this comparative assessment approach by investigating all end-of-life options when decommissioning a steel jacket structure in the North Sea. Eight end-of-life options are available for this jacket: 1. Leave in situ for reuse as a reef; 2. Move to a different location for reuse as a reef; 3. Refurbish, in situ, for alternative use such as renewables; 4. Refurbished but moved location; 5. Recycle in the UK; 6. Recycle abroad; 7. Dispose in the UK; 8. Dispose abroad.

The points are plotted on the matrix according to their potential fuel use and end-of-life options. Relocation or removal decommissioning options use high levels of fossil fuels during the operations that are avoided if the objects are left in situ; likewise, if an object is reused as is, no further inputs in energy are required, thereby avoiding the energy inputs required by recycling for example.

Data from [4] and the data collected for this study clearly show that the more decommissioning activity that takes place, the higher the use of fossil fuels, thereby creating the highest risks of releasing GHG emissions. Furthermore, material end-of-life disposal carries a much higher risk than recycling but recycling still has a significantly higher risk than reuse. The most benign method of decommissioning is to decommission in situ, reusing the structures for other purposes, such as a reef. The most harmful method of decommissioning in terms of emissions is to remove everything and dispose of the resultant waste materials abroad, the method currently most often applied in decommissioning currently, especially in the NAR, as a direct consequence of OSPAR 98/3.

The emissions risk matrix can be used at various scales, from a single decommissioning activity (like the example here) to entire decommissioning programs, as well as decommissioning on a basin scale. Additionally, it could be used for cross-industry planning purposes, for example, reusing OGI infrastructure for other purposes, such as OWI infrastructure.

4. Discussion

Importantly, this study shows that current methods for quantifying GHG emissions due to decommissioning are underreporting those emissions by at least 50%, a serious gap that has consequences for both annual GHG inventories and reporting, as well as our understanding of the causes of global GHG emissions.

The results show that GHG emissions due to decommissioning will increase 200-fold from current cumulative estimates of just over 25 $MtCO_2e$ in 2022 (around 0.5% of annual global GHG emissions) to potentially over 5000 $MtCO_2e$ by 2067 (around 10% of current annual global GHG emissions). This is due to the growth of offshore wind, which requires significantly more infrastructure than the [1] for the equivalent value of the power produced.

The significant growth in future decommissioning GHG emissions revealed by this study illustrates that current decommissioning practices are unsustainable and are not compatible with the legally binding Paris Agreement. This is a significant and serious gap in our understanding of the impact of decommissioning and needs to be recognized and addressed as a serious risk to the Net Zero agenda.

This study shows that OSPAR 98/3 is not compatible with the Paris Agreement going forward due to the sheer mass of infrastructure required by the OWI.

The study demonstrates the importance of a 'close out report' (COR) for accurate GHG emission reporting and to provide a means of testing the accuracy of pre-decommissioning accounting methods and models.

This work further supports the work of [4] and the UN's resource management panel and demonstrates the importance of accounting for material end-of-life destinations, without which GHG emissions are under-reported by a significant amount.

The impact of decommissioning is only one aspect of the total GHG emission impact from the growth of the OWI. This study does not include GHG emissions from (a) the manufacturing, commissioning and building of the infrastructure required by the OWI and (b) the maintenance of said infrastructure over its lifetime. It is likely that the initial commissioning stage will release significantly more GHGs than the decommissioning stage.

The difficulty in gaining access to data demonstrates the need for more transparency with regard to the GHG emissions produced from decommissioning. This data, of public concern, should be made easily accessible to the public, industry and academia. Both individual decommissioning programs and cumulative data should be available, as well as any changes (both positive and negative) revealed by the COR. The data should also be placed into the context of annual decommissioning activity by region and should be easily accessible and understandable to a wide audience, including the general public.

The model assumed a clear sea-bed policy for all infrastructure as the most active/productive OGI and OWI regions require that all infrastructure is removed. Although some regions do allow rig-to-reef programs for OGI infrastructure, this often involves relocating the required structures and, therefore, still produces large volumes of GHG emissions. Furthermore, due to a lack of planning and the long-time scales involved, it is not clear what policies will be in place when decommissioning occurs.

The presented model only looked at CO_2e as no other GHG data were available. Methane, a particularly potent GHG, is likely to have an important role in GHG emissions, especially from plugged and abandoned (P&A) wells.

Current calculation methods are limited to the core activity of decommissioning, those activities that take place in the marine environment, for example, the removal of topsides, pipelines and steel structures. Activities not currently accounted for include onshore cleaning and deconstruction, material preparation for recycling, energy requirements for recycling, onward shipping of materials to their end-of-life location, personnel transport to and from offshore by helicopter and onward onshore travel, vessel and equipment mobilization and transport to the decommissioning site and onwards travel after decommissioning has been completed. This represents a potentially large and significant source of GHG emissions, but it is difficult to quantify because of the lack of data and the huge number of variables, including; where and how deconstruction takes place, power generation required for deconstruction, the recycling or reuse of components and materials and onward destination of international material and recycling markets. Furthermore, these emissions are not (usually) required to be included by the governing body. To try and fill this gap, the 'missing emissions' have been included as a nominal 20% of total emissions. For a detailed discussion on the difficulty of quantifying GHG emissions from shipping, see [4], but clearly, further work is required. P&A operations and any potential leakages of old wells are also not included and likely to cause significant volumes of GHG emissions.

The OGI did not plan for decommissioning when the infrastructure was initially built and installed, and it appears the OWI is also not planning for future decommissioning GHG emissions either. This is a serious oversight that will result in vast volumes of GHG emissions, the scale of which has, until now, not been clearly understood.

Access to data is very limited and is universally very difficult to obtain. Therefore, many assumptions have been made here, and a top-down approach was used. In an ideal world, a wide range of data would be available and used to create the type of complex model required for a full in-depth analysis of how specific decommissioning activity contribute quantitively to GHG emissions. Ideal data include fuel use, material inventories, material and product processing, cleaning and transport and end-of-life route analysis, as well as geographical, climate and weather data. If enough data were available, it would be possible to statistically predict the impact of decommissioning certain objects, i.e., 10 km of pipeline in X environment during Y time of year would likely produce Z volume of emissions. Likewise, a detailed materials inventory would allow us to accurately calculate GHG emissions due to material end-of-life scenarios using the methods described in [4] in combination with detailed life cycle assessment (LCA) GHG emissions figures for each specific material.

Unfortunately, the lack of data also means the usual iterative method of continuous model development has not taken place. Further inputs of data would not only improve the model but would also provide a way to map each activity and mode of operation in terms of the GHG emissions produced. This would provide the industry with easily accessible calculation methods and a way to base decision-making on a GHG reduction strategy. Furthermore, it would allow a detailed picture of GHG emissions due to decommissioning at global, country and basin levels, importantly providing a clear understanding of the scale of the challenge ahead.

There are many opportunities for further study on the impact of decommissioning on cumulative GHG emissions as this is a new field of research, with very few researchers working and very few published studies available. This presents a huge challenge, as the body of scientific evidence is so small that assumptions about processes and activities are frequently made (for example, recycling = good, no matter where the recycling happens or how the energy is produced). OGI decommissioning costs are relatively well defined, but this is not the case with offshore wind, where the necessary processes are only just beginning to be designed. This is concerning as the work presented here shows the significant and increasing impact of GHG emissions due to decommissioning over time.

With the drive to Net Zero and the fast decarbonization that needs to occur, GHG emissions due to decommissioning must be holistically quantified so that the reduction strategy is also quantified. A fully holistic quantification method and a better understanding of cumulative GHG emissions must also be used to inform future decommissioning decisions, policy and planning. In the absence of data, the GHGERM can be used to comparatively assess various decommissioning options.

5. Conclusions

- The work presented here shows that current OGI decommissioning GHG emissions calculation methods are underreporting GHG emissions by at least half.
- It illustrates that the impact of decommissioning offshore infrastructure on global heating is currently significant at 25 MtCO_2e, 0.5% of annual global GHG emissions and that these emissions will increase 200-fold over the coming decades to at least 5 GtCO_2e by 2067; 17 years after Net Zero emissions should have been achieved, which is not compatible with the Paris Agreement.
- The work demonstrates that to understand GHG emissions reduction targets, accurate baseline emissions are required, without which the scale of reduction targets is not understood, nor can effective decarbonization strategies be applied.
- New guidelines are urgently required to allow for accurate pre-decommissioning GHG emissions figures to be calculated and a ‘close-out report’ to be submitted after decommissioning has taken place so that realistic GHG emissions figures can be determined. This should be consistently applied to all industries with infrastructure in the marine environment, including both the OGI and the renewables industry and across all countries.
- New GHG emissions quantification methods should be developed to ensure all consequential GHG emissions from decommissioning are captured and reported accurately, the results of which should be easily accessible and understandable to the general public.
- The results presented here reveal the true scale of the challenge that decommissioning presents and that current decommissioning methods based on clear seabed policies are not compatible with the Paris Agreement.

Author Contributions: A.J.D. led the writing and conceptualization of ideas and designed the methodology with contributions from A.H. and A.J.D. gathered the data for analysis and created the visuals. A.H. supervised and validated the data. A.J.D.: Conceptualization, Methodology, Investigation, Formal analysis, Writing—original draft, Visualization. A.H.: Writing—review & editing, supervision, data validation. All authors have read and agreed to the published version of the manuscript.

Funding: This research is funded by NZTC and the University of Aberdeen through their partnership with the UK National Decommissioning Centre. This work contributed to the NERC-funded FAB-GGR project and UKERC-4 projects.

Data Availability Statement: The authors confirm that the data supporting the findings of this study are available within the article.

Conflicts of Interest: The authors declare that they have no known competing financial interest or personal relationship that could have appeared to influence the work reported in this paper.

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