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Quantifying greenhouse gas emissions from decommissioned oil and gas steel structures: Can current policy meet NetZero goals?

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ABSTRACT

To help achieve global aims to reach Net Zero greenhouse gas (GHG) emissions, a clearly structured method for calculating emissions from decommissioning oil and gas structures is required. In order to understand the GHG consequences of recycling secondary steel from decommissioned structures, this paper presents a new methodology in decommissioning, based on the UN's International Resource Panel (IRP)'s Value Retention method that combines life cycle assessment principles, the waste hierarchy and the circular economy to holistically calculate GHG emissions produced as a consequence of manufacturing primary and secondary steel, manufacturing a product from this steel and the associated transport emissions. The Value Retention Model presented here combines the concept of material value and product value to obtain realistic GHG emission calculations based on end-of-use and end-of-life scenarios, including recycling and reuse options. The results show that reusing a steel jacket structure in situ will retain 55,040 $tCO_2(eq)$ in GHG emissions, not including removal operations or transport emissions. New regulation is urgently required to update the current outdated emissions calculation guidelines, enable the provision of both realistic baseline emissions figures and to provide a mechanism for reporting 'after operations' figures.

1. Introduction

1.1. The decommissioning industry

Decommissioning is the end point of the Oil and Gas Industry (OGI), which explores for and produces hydrocarbons in many locations throughout the globe, both on land (onshore) and in the marine environment (offshore) (refer to Fig. 1.). To extract, produce and process hydrocarbons various structures are required including steel jackets, drilling rigs, topside and pipelines. These structures are required throughout the working life of the field with some in operation for many decades. According to the OGUK (2019), decommissioning represents 10% of overall expenditure of the Oil and Gas industry with around £1.5 billion currently being spent per year on decommissioning activities in the UK alone. Decommissioning not only involves the removal of structures, but also the management of materials removed.

The UK government declared a climate emergency in 2019 in response to the observed effects of climate change and climate science that tells us with ever increasing confidence that the risks to humanity will be severe without radical measures to reduce our greenhouse gas (GHG) emissions to the atmosphere. The UK government enacted the Climate Change Act 2008 (2050 Target Amendment) Order 2019 (Secretary of State, 2019) which stated that the UK must achieve net zero GHG emissions by 2050, this means that all actors must take steps to reduce emissions from all activities and avoid offshoring GHG emissions. This applies equally to the decommissioning sector as well as the wider OGI.

At present the Institute of Petroleum (IOP) 'Calculating energy use and gaseous emissions' guidelines (IOP, 2000; BIR, 2019) are the current best practise for calculating GHG emissions produced during decommissioning operations in the North East Atlantic Region. These guidelines include data and methods which can be used by owners (those companies who have legal responsibility for the structures) in their decommissioning reports and plans, including the environmental assessment, that are required by the appropriate governing body; in the UK this is the Offshore Petroleum Regulator for Environment and Decommissioning (OPRED) which sits within the Department for Business, Energy and Industrial Strategy (BEIS).

The IOP guidelines are 20 years old (Kerr et al., 1999 and IOP, 2000), uses data (such as fuel consumption for vessels) from the mid 1990's and

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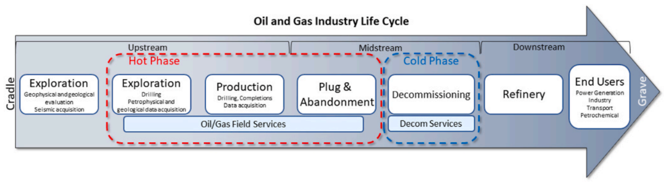

Fig. 1. Oil and Gas Industry Life Cycle showing the three main stages; upstream, midstream and downstream. Decommissioning occurs when there are no longer any fluids (hydrocarbons) flowing in the well and the well has been plugged and abandoned. Adapted from Zekeri et al. (2018) and Bond et al. (2014).

although were originally conceived to be updated regularly, this has not happened. The guidelines attempt to take a life cycle assessment (LCA) approach, but it does this in a very limited way that has some major assumptions, thereby missing large volumes of GHG emissions.

The method for accounting for materials left in situ is one such area that urgently needs to be addressed. The guidelines show inconsistencies, biases and assumptions, for example, the guidelines apply the same values of GHG emissions to steel for both recycling and reuse, whether it is smelted and reprocessed or re-used in its current form; and this is an important distinction in terms of energy requirements and emissions produced.

The guidelines stipulate that if materials are left in situ they are effectively taken out of the ‘materials loop’ and GHG emissions from manufacturing of new primary materials will be needed to replace this material that is ‘lost’. However, this is only applied to materials that can be recycled and GHG emissions associated with those materials (such as plastics and cements) where recycling is not currently available are ignored (Kerr et al., 1999).

For the purposes of this study and to demonstrate the consequence of not undertaking a full LCA approach, the authors have used standard steel as the reference material as significant quantities of steel are used in the extraction, production and processing of hydrocarbons, including steel jackets and steel topsides. Steel is almost infinitely recyclable and high collection rates mean 97% of steel waste is eventually available for recycling (World Steel Association, 2020).

The IOP guidelines also do not factor in the location of waste handling and recycling and do not include GHG emissions produced due to transporting materials to these recycling points. Most materials for recycling in the UK are shipped abroad for reprocessing as there are currently very few industrial recycling centres in the UK and no steel recycling at all. These transportation GHG emissions costs are not included in the IOP guidelines, and no studies have looked at this topic.

To address these issues, this study analyses the assumptions made in the IOP guidelines and provides an alternative to current accountancy methodologies for manufacturing and recycling of steel. Steel is selected for this study as it is the most common material that needs to be managed through the decommissioning process.

The analysis presented here is UK/North Sea centric, but the methodologies can be applied globally as well as potentially proving useful for other industries.

1.2. The primary vs secondary crude steel market

The Institute of Petroleum guidelines (IOP, 2000) make some very significant assumptions about recycled materials (secondary materials) versus primary materials (materials made from new) and the associated GHG emissions.

Steel is infinitely recyclable with (effectively) no materials lost in transition, and according to Broadbent (2016) is an important component of the circular economy. The IOP assumes that all primary steel will be manufactured in a Blast Furnace (BF) or Basic Oxygen Furnace (BOF) and all recycled (secondary) steel will be processed in an Electric Arc Furnace (EAF). It also assumes that EAF always uses electricity produced by renewable sources, a huge simplification of the reality as EAFs are often coal powered (World Steel Association, 2020).

According to the World Steel Association (2020), not only is there is a world shortage of scrap steel, but BF/BOF use a significant input of secondary steel in the manufacture of primary steel. A Blast Furnace (BF) or Basic Oxygen Furnace (BOF) can be charged with as much as 30% steel scrap and an Electric Arc Furnace (EAF) can be charged with 100% steel scrap, but there is no consistency or standard globally and the amount of steel scrap used depends on the type of steel needed and how much scrap is available. According to the Bureau of International Recycling (BIR, 2019) the global ratio of steel production in a BOF versus an EAF is 70% and 30% respectively, confirming the World Steel Association statistics, however He et al. (2017) state that 90% of steel is produced through the BF/BOF route in China.

In 2019 crude steel production hit 1869 million tonnes (BIR, 2019), an increase from the 2018 volume of 1808 million tonnes, these numbers have been growing year on year, with the exception of 2009 when the global economic crash had an impact on steel requirements and therefore production.

According to the BIR (2019) the volume of steel recovered for recycling, or steel scrap was 105 million tonnes in 2018 compared to 1808 million tonnes of crude (primary) steel production. The difference in these figures, a total of 1703 million tonnes shows there is a significant gap between steel scrap availability and steel needed for new products. This trend is set to continue as the market for steel continues to grow. China is by far the largest producer of steel with 996 million tonnes produced in 2019 and 920 million tonnes in 2018 followed by India at around 10% of this figure (Fig. 2).

The longevity of steel also has an impact on the volume of steel collected for recycling. Steel is very stable and is often not available for recycling and scrap for a number of years (depending on the use and design of the product). In terms of decommissioning, we know that structures such as jackets and platforms are designed to remain in use in the marine environment for decades during the operational part of the oil and gas industry.

We do not know the percentage of steel lost to erosion and corrosion in the marine environment, the IOP guidelines assume no steel is lost and the volume of materials used is considered exactly the same as the volume of materials at the start of the operational life. There is currently no published data to support or argue this claim, although some research has recently begun to question this. For the purposes of this report, it will be assumed the amount of material at the beginning is the same as that taken out. We must assume that whilst the structure is operational a cathodic protection system (either passive or active) is employed to maintain the integrity of the structure.

It has been very difficult to gain access to detailed data related to decommissioning operations and the data the authors did get access to does not itemise emissions in any detail, so it is impossible to separate emissions associated with particular operations, materials and transport, except in the few reports that have itemised these figures in a limited way. The authors have access to the IOP guidelines and as these are the suggested methods for the operators who are compiling decommissioning plans and calculating the GHG emissions figures in the North East Atlantic Region including the UK, it must be assumed that these guidelines were used in these calculations, along with the suggested data points (for example rate of fuel use for a particular vessel) for estimations of GHG emission presented for the decommissioning options in the Environmental Assessment required by regulation for each decommissioning project.

1.3. Research methodology

The methodology for modelling GHG emissions from steel production and manufacturing uses a life-cycle assessment (LCA) approach to holistically account for both direct and indirect GHG emissions from a

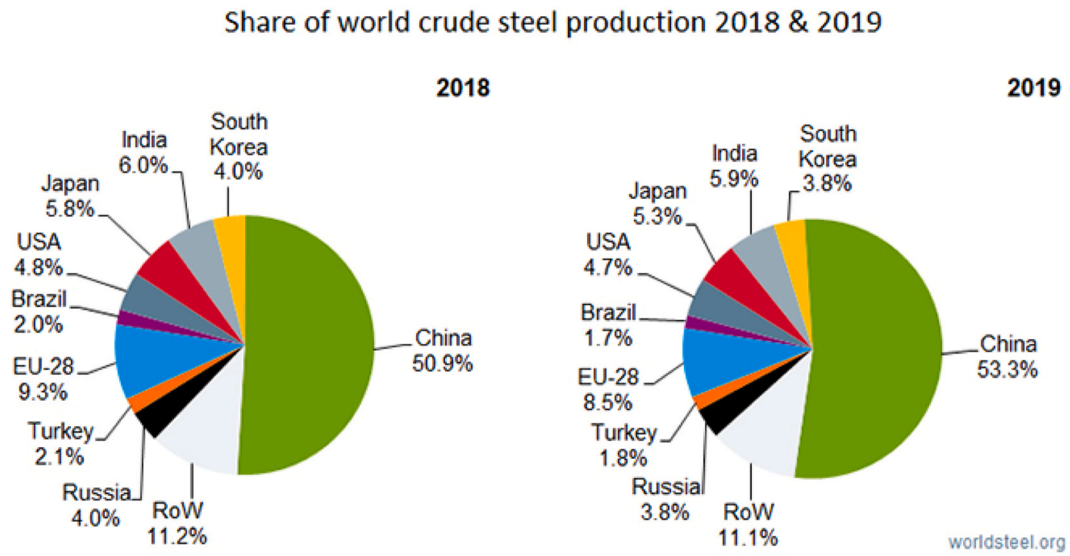

Fig. 2. Share of world crude steel production in 2018 and 2019, note that EU-28 is the EU plus the UK. From World Steel Association (2020).

cradle-to-grave perspective. Although decommissioning is the end point of the OGI and therefore fits within the whole OGI life cycle, responsibility for the accounting of GHG emissions due to end-of-life endpoints of materials used during the OGI life cycle are within the decommissioning remit (IOP, 2000).

Fig. 3 illustrates the life cycle of upstream structures (such as steel jackets) during their useful life, at the end of which the structures are expected to be fully removed (in the UK), compared to the life cycle of the OGI as a whole. End-of-life material end-point decisions need to be made and Fig. 3 illustrates the alternative solutions according to the waste hierarchy, a way to quickly evaluate material end points from a sustainable perspective (Hansen et al., 2002). The study presented here takes a top down approach to quantifying GHG emissions from direct emissions, indirect emissions and transport emissions for both the primary and secondary steel route. A simplified life-cycle diagram is presented in Fig. 4 for primary (crude) steel and secondary (recycled) steel.

2. Results

2.1. Primary vs secondary crude steel manufacturing GHG emissions

The IOP figures for GHG emissions associated with manufacturing and recycling steel is 1889 kgCO_2(eq) per tonne of new steel produced (primary steel) and 960 kgCO_2(eq) per tonne of steel recycled (secondary steel) (IOP, 2000). This data comes from two sources; A paper referenced as OLF 1996 and a German book entitled ‘A guide to the environment’ by Buwal 1990, both of which appear to be out of print and neither of which are currently available.

According to the World Steel Association (2020) for every tonne of steel produced, 1.85 tCO_2(eq) is emitted. This figure is consistent with the IOP guidelines figure of 1889 kg$CO_{2(}$eq) per tonne of primary steel produced. Most academic papers use the World Steel Association figure, for which there is a published method, and is consistent with ISO 20915: ‘Life cycle inventory calculation methodology for steel products’ (ISO, 2018), refer to Fig. 7 below. What isn’t as clear or as well defined are the GHG emissions associated with steel production in an EAF, the following section aims to address this gap.

2.2. Electric arc furnace steel manufacturing GHG emissions

According to Yu. N. Chesnokov et al. (2014) the GHG emissions due to steel manufacturing in an EAF is 734 kgCO_2(eq) per tonne of steel. Significantly, these direct emissions - resulting from processes that exhaust GHGs (predominantly CO_2) from the EAF meltshop and depend

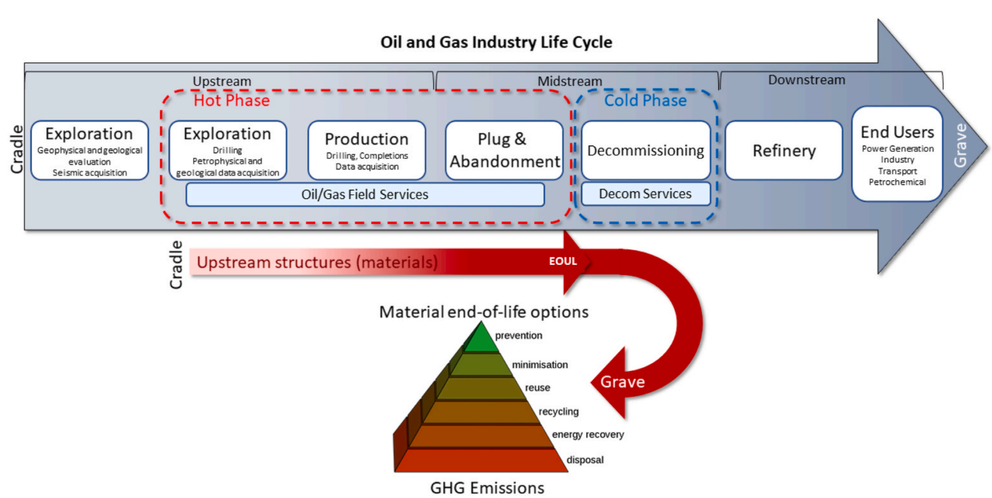

Fig. 3. Oil and gas industry life cycle (grey arrow) with the upstream structures life cycle illustrating end-of-life (EOL) endpoints and relative GHG emissions for each end-of-life option. OGI LC adapted from Zekeri et al. (2018) and Bond et al. (2014), waste hierarchy adapted from Hansen et al. (2002).

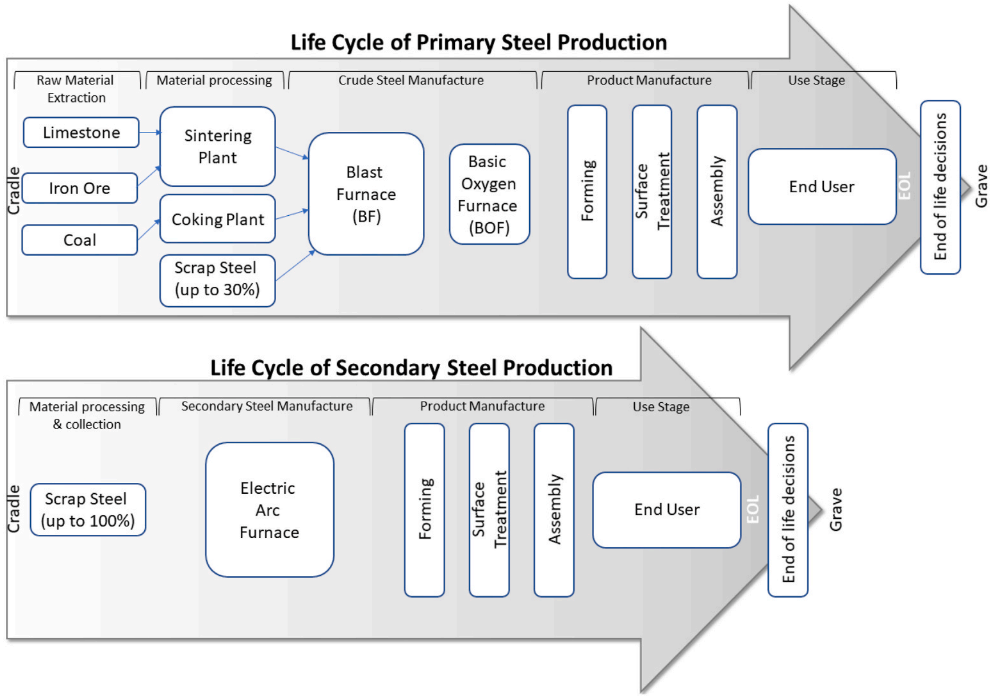

Fig. 4. A simplified life cycle of primary and secondary steel production and product manufacturing showing the cradle-to-grave approach taken here. Adapted from Stahl (Accessed Dec 2020).

on the volume of hydrocarbons in the charge, the burner, the efficiency of the processes, as well as the carbon content of the steel scrap, graphite or other additives used (Thomson et al., 2000) - do not include GHG emissions due to the production of electricity consumed by the EAF, considered by Chesnokov as "indirect emissions".

These "indirect emissions" are in fact consequential emissions that would not have been made if the steel had not been processed and must be included to properly analyse the GHG emissions produced due to the EAF processes, in other words, it's carbon footprint. According to Thomson et al. (2000), indirect GHG emissions sources can be more significant than direct emissions from the EAF, with the production of electricity used in the EAF being the most important indirect GHG emissions source.

The GHG emissions associated with generating electricity for use in an EAF is directly linked to the type of fuel the power plant uses and the thermal and generating efficiency of the plant. Renewably produced electricity from wind, solar or hydropower will significantly reduce the overall carbon footprint, but is not zero. If, on the other hand, fossil fuel is used to power the electricity generation, a significantly larger carbon footprint must be calculated. Fig. 5 illustrates the energy mix of the UK and China. China produces around 57% of its electricity through burning coal, whereas the UK is dominated by natural gas at 37% of the total with very little coal use at around 2%.

Fig. 6 shows the CO_2(eq) per tonne of steel produced from power plants using various sources as the main fuel type.

We can clearly see there is a significant difference in the carbon footprint of each power plant depending on the type of fuel used. Coal powered power plants produce 583 $kgCO_2eq$ per tonne of steel and renewables such as wind producing just 3 $kgCO_2eq$ per tonne of steel. This should be taken into consideration when calculating the emissions for decommissioning and it has a large impact on recycling emissions calculations.

If we assume the figure of 734 $kgCO_2$(eq) is correct for direct GHG emissions associated with the EAF process, then add the emissions associated with the production of electricity (indirect emissions), we have figures that vary significantly from source to source with the coal

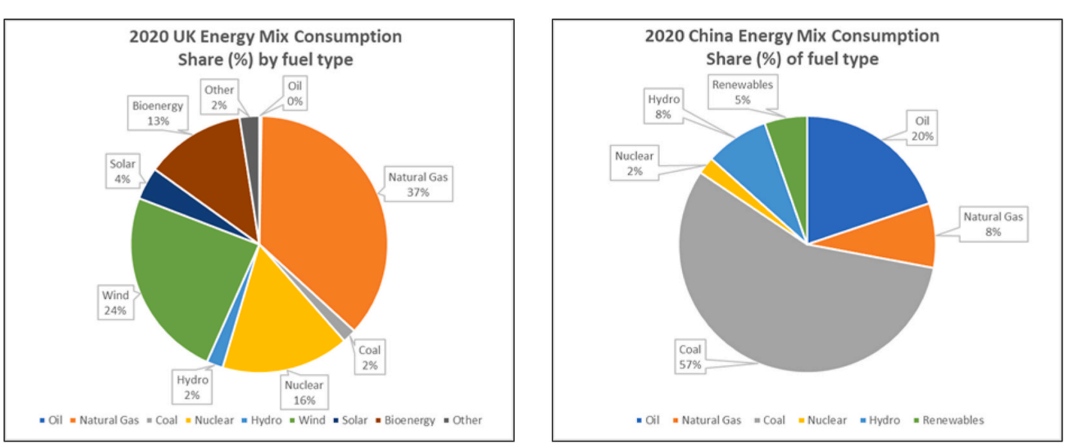

Fig. 5. The electricity generation mix in China in 2020 (source: BP plc, 2021; China Electricity Council 2020) and the UK in 2020 (BEIS, 2021).

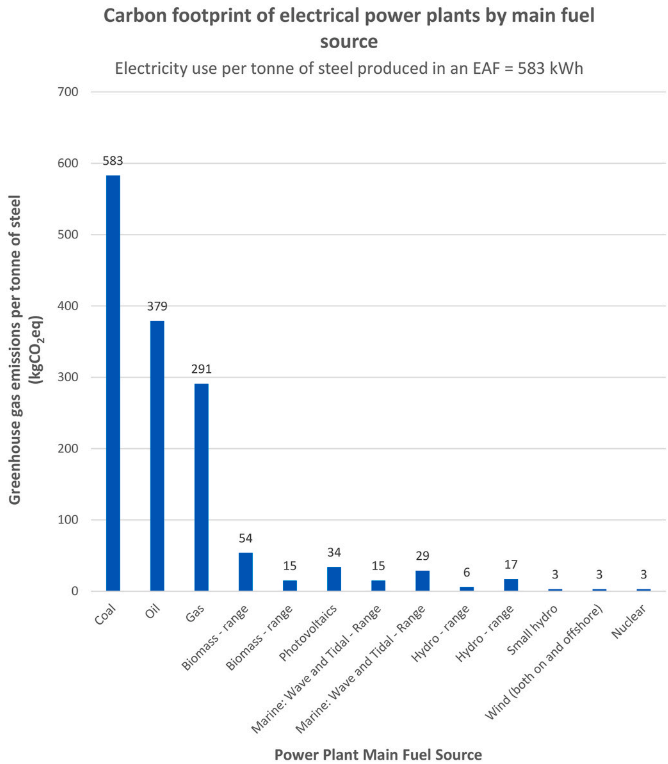

Fig. 6. Carbon footprint of power plants by fuel source for producing electricity for use in an Electric Arc Furnace EAF (https://www.parliament.uk/globalassets/documents/post/postpn268.pdf, 2020), EAF figure of 583 kWh from Navas-Anguita et al. (2019).

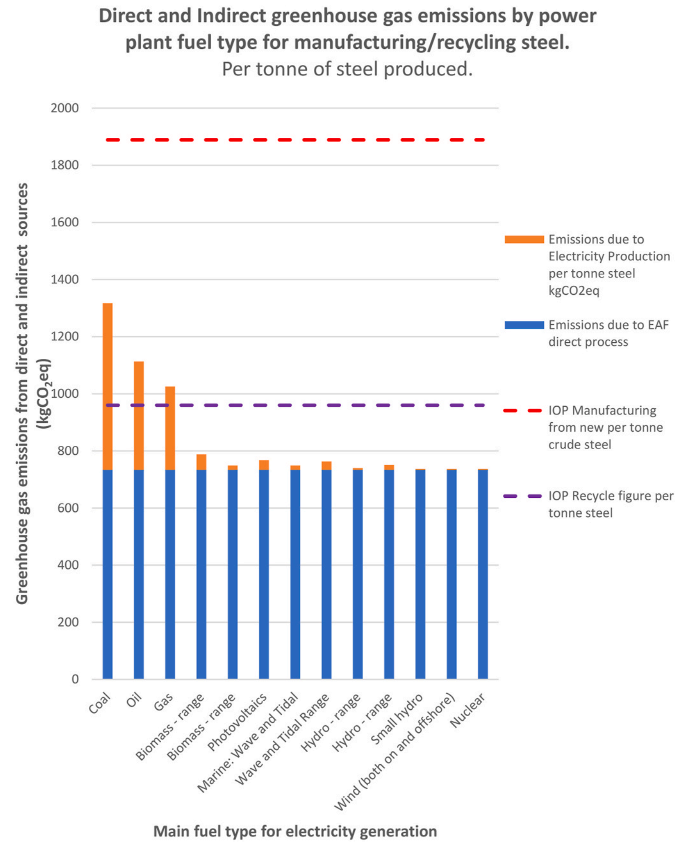

Fig. 7. Carbon footprint of EAF process plus the carbon footprint of electricity generated to produce 1 tonne of steel. (Parliament (2020), Chesnokov et al., 2014), Navas-Anguita et al. (2019).

powered stations producing substantially and significantly more GHG emissions than all other sources of fuel. Nuclear and wind energy produce the lowest GHG emissions. Furthermore, the location of the EAF is important as some countries continue to be dominated by coal powered electricity. For example, a significant proportion of electricity in China is produced using coal powered plants (57% of electrical output in 2020), and India produces almost 70% of its electricity using coal (Tiewsoh et al., 2019). An idealised example of the carbon footprint of a conventional EAF by contry energy mix is presented in Fig. 8.

2.3. GHG emissions due to transportation of materials to recycling centres

Another significant gap in the IOP guidelines is the lack of accounting for GHG emissions from transporting materials to recycling centres. Steel scrap is mainly recycled in China, followed by India and occasionally Turkey (see Fig. 9). In terms of decommissioning, steel is either taken onshore where it is cut, processed and prepared for transportation or it can be towed whole or in large pieces directly to the recycling centre. A large steel jacket for example can be towed from its operational location in the North Sea to an electric arc furnace in Turkey.

GHG emissions produced from maritime shipping are currently not included in the United Nations Framework Convention on Climate Change (Endersen et al. 2003), nor the Paris Agreement (Paris Agreement, 2015). A fractious UN meeting in October 2020 to agree new reducing policies ended with IMO agreeing to only increasing maritime shipping emissions of 14% by 2030 compared to a 'business as normal' estimate of increasing emissions by 15% by 2030 (Degnarai, 2020). According to Hoen et al. (2017) GHG emissions from shipping is responsible for 3% of all global GHG emissions at around 1 $GtCO_2(eq)y^{-1}$ making shipping the 6th largest contributor to global GHG emissions (Degnarai, 2020).

Within this framework it is difficult to find reliable and realistic GHG emissions figures for vessels with reported GHG emissions from marine transport wildly variable. GHG emissions figures for maritime transport of up to around 135 $gCO_2(eq)km^{-1}t^{-1}$ are reported by the European Environmental Agency (EEA) (2017). This figure has been arrived at by including all statistically significant voyage impacts including weather and sea state, speed of travel, currents and the weight and bulk of the items being shipped. Significantly it includes all vessel types of all ages, rather than distinguishing by type, size, age or engine for example bulk carries, container ships and cruise vessels which would all be assigned this figure, even if there are considerable differences in their operational modes. The IMO (2015) report GHG emissions figures of 3 $gCO_2(eq)$ $km^{-1}t^{-1}$, but this figure is for Ultra Large Container vessels (ULCV) with loading capacity of over 20,000 teu (twenty-foot container equivalent) and represents the technical specification which is obtained under perfect calm and optimal fully laden conditions. The nature of these super-sized container ships means that economies of scale will play a part in reducing the overall GHG emissions figures per tonne of commodities carried and per distance travelled. However bulk scrap is not usually transported in ULCV's.

Technical efficiency figures for different vessels are available, but these data represent GHG emissions as released by the ship manufacturing industry and like the ultra large container vessels, represent a 'perfect voyage scenario' under perfectly calm and fully laden conditions where significant statistical influences such as speed of vessel, wind and current direction and weight and bulk of materials transported are ignored.

Several authors have developed detailed models to try and understand the volume of GHG emissions from international shipping. Endresen et al. (2003) used calculated bunker fuel data together with Automated Mutual-Assistance Vessel Rescue System (AMVER), whereas Trimmer and Godar (2019) used a much more detailed methodology and

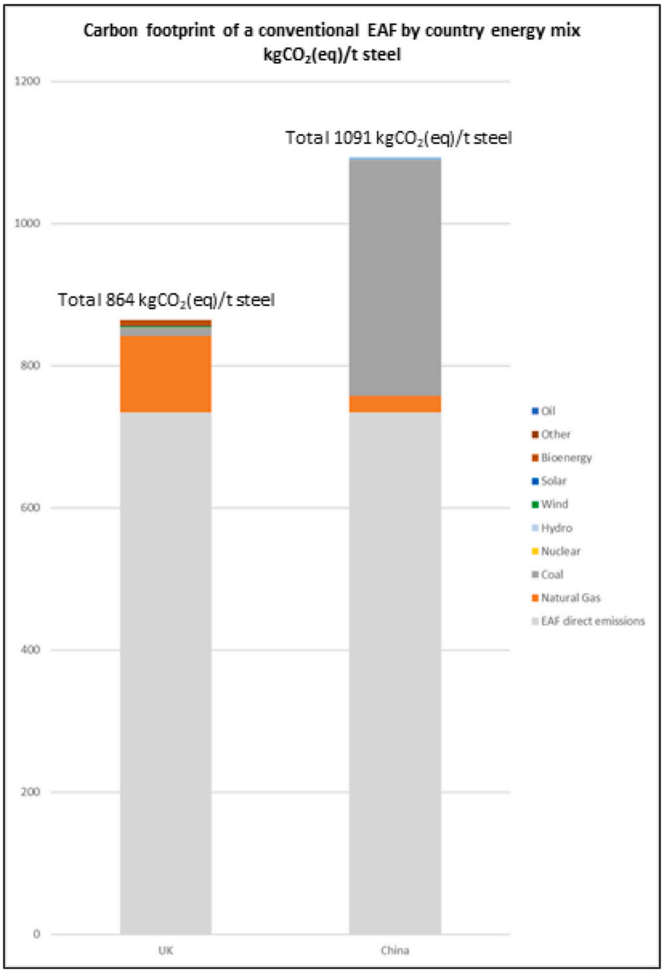

Fig. 8. This graph shows the carbon footprint of a conventional EAF by energy mix for the UK and China to produce one tonne of standard steel in kgCO2(eq)/t steel. This represents an ideal scenario of 100% steel scrap from OGI decommissioning to be recycled sent to an EAF. This ideal scenario would not happen in reality as there is no way to control the end location of steel scrap as it enters the global steel market. Adapted from Parliament (2020), Chesnokov et al., (2014), BP (2021), China Electric Council (2020) and the UK in 2020 (BEIS, 2021).

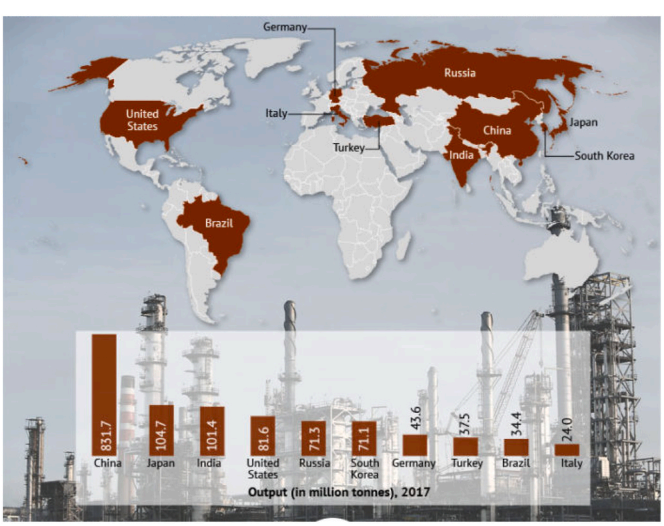

Fig. 9. Top ten steel manufacturing countries for Basic Oxygen Furnace (BOF), Blast Furnace (BF) and Electric Arc Furnace (EAF). From Maps of World (2018).

data driven approach by using Automatic Identification System (AIS) data on the ships position, bearing, draft, and speed, along with estimates based on the traded commodity for mass and bulkiness, detailed journey descriptions (for example type and age of vessel and route of vessel) in conjunction with a harmonised commodity description and coding system developed by the World Trade Organisation. They found that a lack of reliable data and poor disputed methods for assigning responsibility for shipping emissions to different countries, traders, producers, consumers and transport companies has an impact on data collection, quality and reporting. This describes the exact challenge of the decommissioning industry; with the calculations of GHG emissions associated with transporting decommissioned steel in that not only are the operations not well defined statistically, the complexity of operation, and end points of materials and scrap is not so well defined.

Bouman et al. (2017) used a figure of 25 $gCO_2(eq)nm^{-1}t^{-1}$, equivalent to 13.5 $gCO_2(eq)km^{-1}t^{-1}$ but again this figure does not include all the complexity and subtleties associated with accurate GHG emissions calculations. Aulinger et al. (2015) describe how until recently GHG emissions estimates were done by estimating fuel consumption by fuel sales figures and then applying the specific emissions factors to this. They also agree with Trimmer and Godar (2019) in that AIS can be used to accurately track ship movements and engine loads and Enersen et al. (2003) found that calculated bunker fuel was generally in agreement with international sales statistics.

Wang et al. (2019) unusually measured GHG and other air pollutant quantities from 50 different vessel types under real world conditions and found that the age of the vessel has a significant effect on emissions figures, with older vessels showing significantly higher GHG emissions (which can be as high as around 70%) than the youngest ships.

According to Schim van der Loeff et al. (2018) there is a significant lack of reliable emissions data, but an assessment can be made based on cargo type (commodity type), country and companies by linking per vessel cargo, individual journeys, vessel specifications and details on their movements as well as operations. Vettor et al. (2018) found that environmental loads are among the most important factors on fuel consumption under navigation with wind alone potentially increasing fuel use by 6%. Szelangiewicz et al. (2014) found that high complexity models are needed to accurately optimize the vessel route and thereby minimise fuel consumption, which in turn will minimise GHG emissions.

THETIS-MRV is an online database for the purposes of accurate monitoring, reporting and verification of carbon dioxide (CO_2) emissions and other relevant information from ships arriving at, within or departing from EU ports (and the journeys between) under the jurisdiction of a Member State, under Regulations (EU) 2015/757. The database includes the technical specifications for specific vessels over 5000 tonnes and includes everything from cruise liners to ultra large container ships. Significantly this database also shows a wide spread of emissions values for vessels, for example the data spread for container ships is 8.4–202 $gCO_2(eq)nm^{-1}t^{-1}$ which is equivalent to 4.5–109 $gCO_2(eq)km^{-1}t^{-1}$.

To put this into context using the data above for container ship GHG emissions, to transport the entire Heather Alpha jacket to China would cause GHG emissions in the range of 1650–39,800 $GtCO_2(eq)$ for the entire trip (of 12,321 nm). This is a staggering range of potential GHG emissions and clearly shows that reported emissions from marine transport are very far from being well defined, and that to quantify GHG emissions from transporting end-of-life decommissioned materials, a detailed analysis of the statistically relevant variables must be undertaken.

Furthermore, what this wide data spread tells us is that there is significant knowledge gap in the reporting of GHG emissions due to shipping and that the impact of ship size, sailing route, number of stops, age of ship, efficiency of engine, fuel use, speed, weather and sea state, currents and winds, bulkiness of commodity and number and type of ship manoeuvres should all be taken into consideration so that an accurate account of GHG emissions due to shipping is calculated.

2.4. Total GHG emissions for recycling steel

The GHG emissions for reprocessing steel in an EAF includes both direct emissions (those produced from the manufacturing processes) and indirect emissions (those associated with the production of electricity). The data shows that if the electricity used in an EAF is produced from non-renewable sources, especially coal, the GHG emissions saving gap between recycling and manufacturing, in other words production of secondary and primary materials is relatively small at only 572 $kgCO_2$(eq) per tonne of steel.

As steel scrap enters the global steel market it is not possible to determine where the scrap will be reprocessed. As steel scrap represents only 10% of the global steel market, there is no guarantee that the scrap will be reprocessed in and EAF. Statistically the scrap is more likely to be reprocessed in a BF or BOF as globally 73% of primary is produced via the BF/BOF route and 27% is produced via the EAF route (World Steel Association 2020) and scrap is not kept separate from primary steel production but is in fact an essential addition to the primary steel production.

It is clear that there is not currently enough data, nor a complex enough model, to make a confident GHG emissions calculation from transporting materials from decommissioned oil and gas structures. This gap in our knowledge could be hiding a significant GHG emissions contribution and needs to be addressed with some urgency.

2.5. Steel product manufacturing GHG emissions

A further large and significant gap is the GHG emissions associated with manufacturing a product from the primary or secondary steel. In the OGI products manufactured for use include steel jackets and topsides, the design and manufacture of which will make a significant contribution to GHG emissions but are not currently included in the calculations. This is estimated to double the emissions but depends on the complexity of the structures and the grade and degree of reprocessing of the raw steel into plate, bar and pipe forms.

The collection of materials for recycling should be encouraged, especially if the philosophy of life-cycle-thinking (LCT) and waste hierarchy is put at the centre of the decommissioning approach and GHG emissions calculations, but the methods used in the IOP do not allow for a mechanism for this, nor do they reflect the realities of the need for collection of waste material. Furthermore, the IOP guidelines do not make enough of a distinction between material endpoints. The IOP guidelines apply the same value to steel for recycling or reuse, whether it is smelted and reprocessed or re-used in its current form; and this is an important distinction, especially in terms of energy requirements and emissions produced.

Most academic papers use the Word Steel Association figure of 1.85 tCO_2(eq) (World Steel Association, 2020), for which there is a published method, and is consistent with ISO 20915: 'Life cycle inventory calculation methodology for steel products' (see Fig. 10). This figure includes GHG emissions from extraction or mining of raw materials (coal, iron and limestone) and transport and processing (sintering and coking). Crucially and highly significantly, this figure does **not** account for emissions produced from the design and manufacture of a product from this crude steel. The figures for this are hard to find and depend on the nature and complexity of the product and how many processes will be employed during this final manufacturing stage. The more complex and energy intensive this stage, the higher the volume of emissions produced.

Hauke et al. (2017) found that the total GHG emissions to manufacture a final product is 54% for crude steel production and 46% for product manufacturing and construction. Where the emissions figure for manufacturing of crude steel is 1.85 $tCO_{2(}$eq) per tonne of steel produced, the final product construction emissions allocation are estimated to be a further 1.59 $tCO_{2(}$eq) per tonne of steel product. This figure is generalised and is not specific to decommissioning. The complexity of design and manufacturing process will have an impact on emissions produced with the more complex and technically challenging, the higher the impact on emissions. However as there is a serious lack of data sharing within the OGI, along with the associated supply chain, it is impossible to calculate a more accurate figure at this time.

This is a significant data gap, as more detailed and decommissioning focussed GHG emissions figures for the product manufacturing stage would allow us to apply a much more focussed and detailed figure for these GHG emissions. Furthermore, in the case of the manufacturing of more specialised crude steel, a more accurate figure should be calculated based on data available from sources such as the ICE database (https://circularecology.com/embodied-carbon-footprint-database.html) (Embodied Carbon – the ICE Database, 2021).

2.6. Mechanism for accounting for material and product manufacturing and processing GHG emissions

The International Resources Panel (IRP), part of the United Nation's Environmental Program and was established in 2007 to provide scientific assessments on the use of natural resources and its environmental impact over the full life cycle (Nasr et al., 2018). According to Oakdene Hollins (2020) the term 'value retention' was first adopted by the IRP after the completion of a global study looking at business processes designed to keep products in use for an extended time by capturing the economic value and environmental impacts of the products at the end of their useful life. According to Nasr et al. (2018) to understand the environmental and economic benefits of circular economy practises which seek to retain value within the economic system (value-retention processes, VPRs) includes direct reuse, repair, refurbishment and remanufacturing as well as recycling (see Fig. 11). However, it is important to note that not all VRPs have equal impacts and will depend on the specific VRP deployed (see Fig. 12). This is discussed further in the next section. The benefits of using VPRs is that they offer opportunities to achieve significant value-retention, reducing environmental

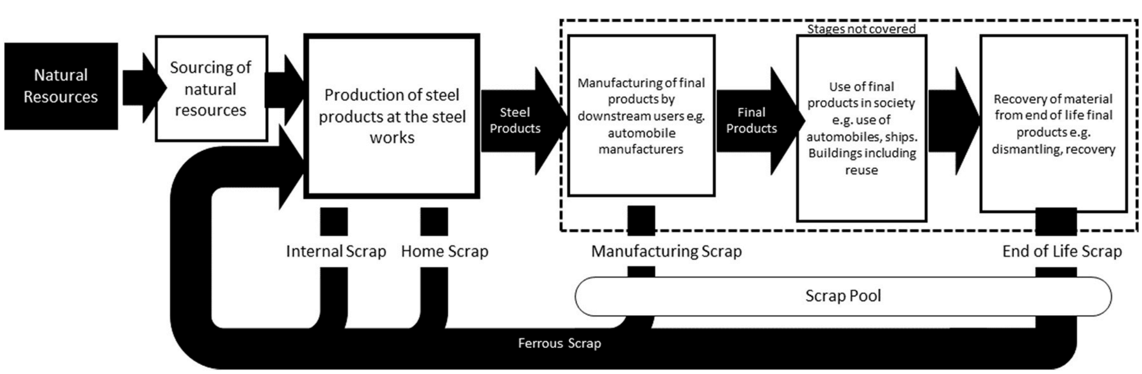

Fig. 10. Schematic diagram of the life cycle of steel showing included stages as well as those excluded. From ISO 20915:2018 (2018).

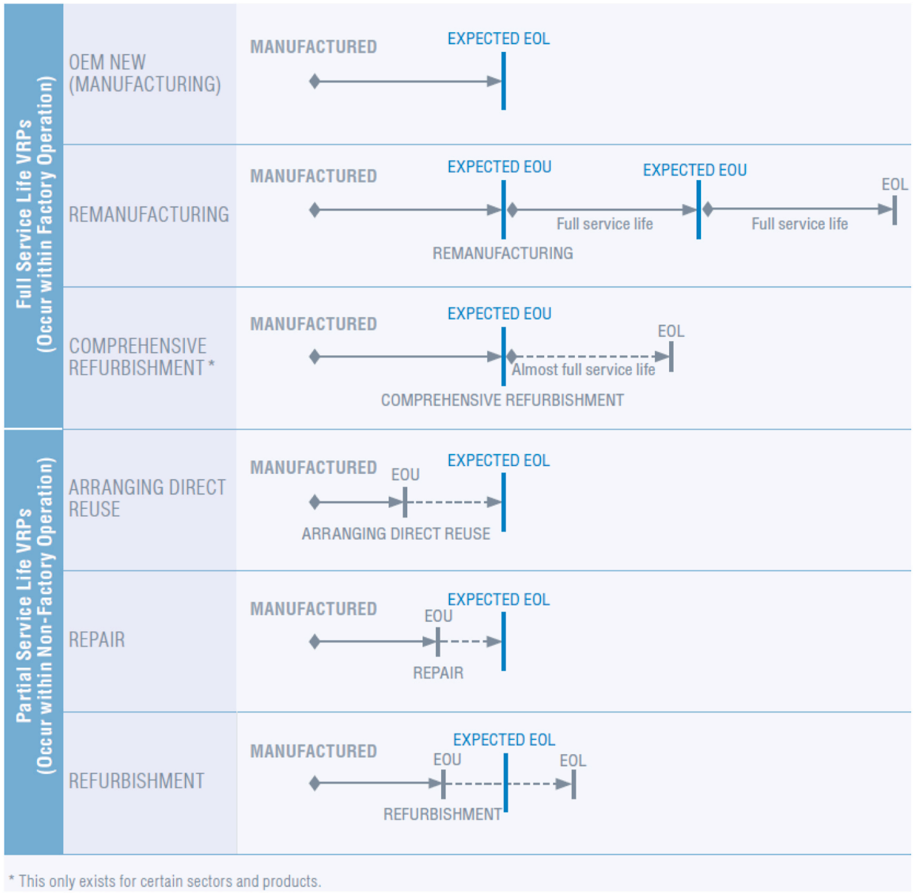

Fig. 11. Description of value-retention potential of Value-Retention Processes (VRPs). The original equipment manufacturer (OEM) refers to the items manufactured, assembled and installed during the construction of a new product.

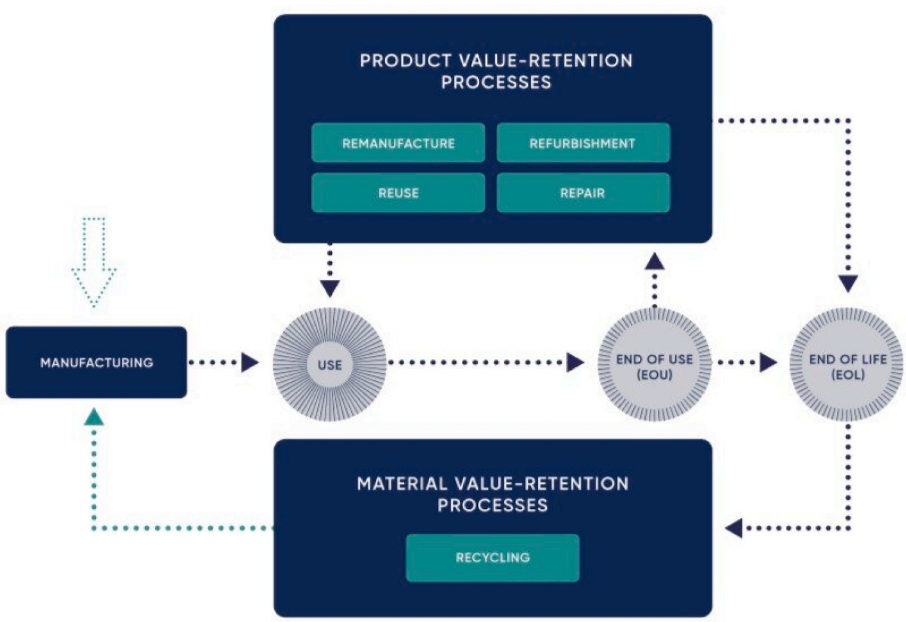

Fig. 12. Product life cycle using the principles of value-retention to select the most effective strategy for retaining the highest value from the materials and products. From Oakdene Hollins (2020).

impact whilst also creating economic opportunities for cost reduction (Nasr et al. 2018).

The importance of Value Retention Processes (VRPs) was further highlighted by the G7 Alliance of Resource Efficiency Workshop 'Actions to scale-up Value Retention Process Business Models for Consumer Products' which was held in November 2019. The workshop summarised that VRP Business Models have remarkable potential for delivering climate and biodiversity goals together with sustainable economic growth and resilience (G7 Alliance, 2019) and that scaling up VRP business models contributes to joint achievement of climate mitigation and reduction of biodiversity loss.

According the G7 Alliance on Resource Efficiency (2019) national economic and policy frameworks are not aligned with VRP businesses as they have been designed to support the linear economy. To promote VRP, changes to the current economic framework are needed, including the addition of specific support policies. This is certainly the case in OGI decommissioning as the IOP methodology is based on the linear take-make-waste model and does not allow for any extended life options such as reuse.

Hauke et al. (2017) applied the principles of value-retention in their life cycle assessment of steel making, by the use of 'material value' and 'product value'. Material value is the embedded energy and emissions from the manufacturing of primary steel, including mining of iron ore, preparation of the ore to extract pig iron, mining and processing of coal and other necessary raw materials, the transportation of these raw materials to the production site as well as energy use and emissions from the Blast Furnace (BF), Basic Oxygen Furnace (BOF) or Electric Arc Furnace (EAF). The product value is the embedded energy and emissions associated with processing the crude steel and creating a final product and includes activities such as milling, rolling and shaping.

Hauke et al. (2017) describe their approach as the "recycling potential approach" as it takes account of a material's complete industrial cycle, in an end-of-life approach, consistent with the philosophy of the UN's IRP VRP and life-cycle-thinking. Unlike the IOP guidelines this method includes all aspects of the life-cycle-assessment, rather than ignoring GHG emissions from some inputs, such as GHG emissions produced during manufacturing of a product from crude steel.

This study provides a more complete picture of the emissions associated with manufacturing both primary and secondary steel by addressing the assumption in the IOP that all steel sent for recycling is reprocessed in an EAF and all primary steel is produced in a BF/BOF, as this is not the case. The Value Retention (VR) Model is presented as a new methodology for calculating GHG emissions in OGI decommissioning based on the UN's Value Retention Processes (VRPs). The model distinguishes between End of Use (EOU) and End of Life (EOL) scenarios by including reuse, repair, refurbish and remanufacture as separate processes that retain the value embedded in both the material manufacturing and product manufacturing stages. As this study has shown, both the manufacturing of crude steel and manufacturing a product from this crude steel produces large and significant volumes of GHG emissions. Furthermore, this study has shown that it is currently impossible to track the end-point of the steel waste as the steel enters the global market and therefore this VR Model is presented here to more accurately estimate the GHG emissions from each stage of the life-cycle, effectively filling the gaps of the IOP method.

2.7. IOP Heather platform example

The IOP guidelines used a published decommissioning plan as a worked example, namely the decommissioning of the Heather Alpha platform, which included the decommissioning of a 16,000 tonne steel jacket. The current IOP method for calculating GHG emissions from materials at the end of their useful life uses the linear take-make-waste model and not only leaves large gaps in emissions reporting, but also makes very large assumptions about material flows after the end of its useful life, namely that all steel collected will be sent for recycling via the EAF route. This study has shown that this is simply not the case as there is no way to guarantee that the steel will be reprocessed in an EAF (steel scrap represents around 10% of steel requirements globally). The figure for creating new steel to replace steel decommissioned but not recycled is 1,889kgCO_2(eq) and importantly does not include GHG emissions due to manufacturing the end product from crude steel and therefore underreports the emissions figures significantly.

Fig. 13 a) illustrates the current IOP method based on the linear take-make-waste model for GHG emissions calculations for the end point of decommissioned steel for both the recycling route and replacement route and represents a significant simplification of processes and material end-points as it assumes all steel scrap is sent for recycling via the EAF route which in reality does not happen. The IOP GHG emission figures for the steel recycling is 960kgCO_2/t steel x 16,000t steel = 15,360tCO_2(eq) and the replacement of the steel is 1,889kgCO_2/t steel x 16,000t steel = 30,244tCO_2(eq).

Fig. 13b) illustrates the new VR model where the consequences of various end-of-useful life and end-of-life decisions have different impacts on GHG emissions and can be easily quantified once a material value and product value have been established. This can be done either through modelling (like here) which takes a top-down approach, or through a bottom-up approach with a detailed examination of industry or product specific data where it is available.

Fig. 14 illustrates the Value Retention Model for four decommissioning options (end-of-use or end-of-life decisions) by showing the material flow pathways (pathways are shown in blue) for each end-of-use decision with corresponding GHG emissions produced. Fig. 14a) In this scenario the entire steel jacket remains in situ for reuse either by the OGI or another industry for example as a base for a wind turbine in the renewable industry. As no new processing of the product or material is required, both the material value and product value are retained and therefore zero GHG emissions are assigned. In reality there would be some GHG emissions associated with maintenance and monitoring, but this is probably very small in comparison to the GHG emissions produced during the material and product manufacturing stage. These small scale GHG emissions from monitoring and maintenance are not included here due to lack of data but should be included in future GHG emissions calculations.

Fig. 14 b) Refurbish in situ. Like reuse in situ, this scenario retains both the material value and product value. The refurbishment of the steel structure will produce GHG emissions but in comparison the material and product values these will be comparatively small.

Fig. 14 c): Remove and recycle the entire steel structure. The product value is lost because the steel jacket will be reformed and reprocessed into secondary crude steel. The material value would be retained as all the steel (the material) is still available, and the high intensity GHG emissions associated with the manufacturing of primary crude steel such as mining and processing coke, pig iron and limestone is not needed to be undertaken.

Fig. 14 d) Dispose of entire steel structure. This last scenario illustrates the GHG emissions caused by disposal of the steel structure, with the loss of both the material value and product value. This example illustrates the large GHG emission footprint of disposal with a calculation of 55,040 tCO_2(eq) which equates to the loss of material value of 1.85tCO_2(eq) per tonne of steel (1.85tCO_2(eq)/tsteel x 16,000 tonnes = 29,600tCO_2(eq)) and the loss of the product value, estimated to be 1.59 tCO_2(eq) per tonne of steel (1.59tCO_2(eq)/tsteel x 16,000 tonnes = 25,440 tCO_2(eq)).

3. Discussion

This study demonstrates the need to approach GHG emission calculations from a life cycle thinking (LCT) perspective to holistically include all sources of GHG emissions from a cradle-to-grave approach and confirms that by not following this methodology large and significant sources of GHG emissions can be (and have been) missed. The example of reporting of GHG emissions from EAF operations is significant because it demonstrates that by not including all indirect emissions (in this case the emissions associated with producing electricity), unrealistic and underreported GHG emissions figures will be calculated.

The results show that data and methodologies in the Institute of Petroleum (IOP) guidelines (2000) used to calculate GHG emissions

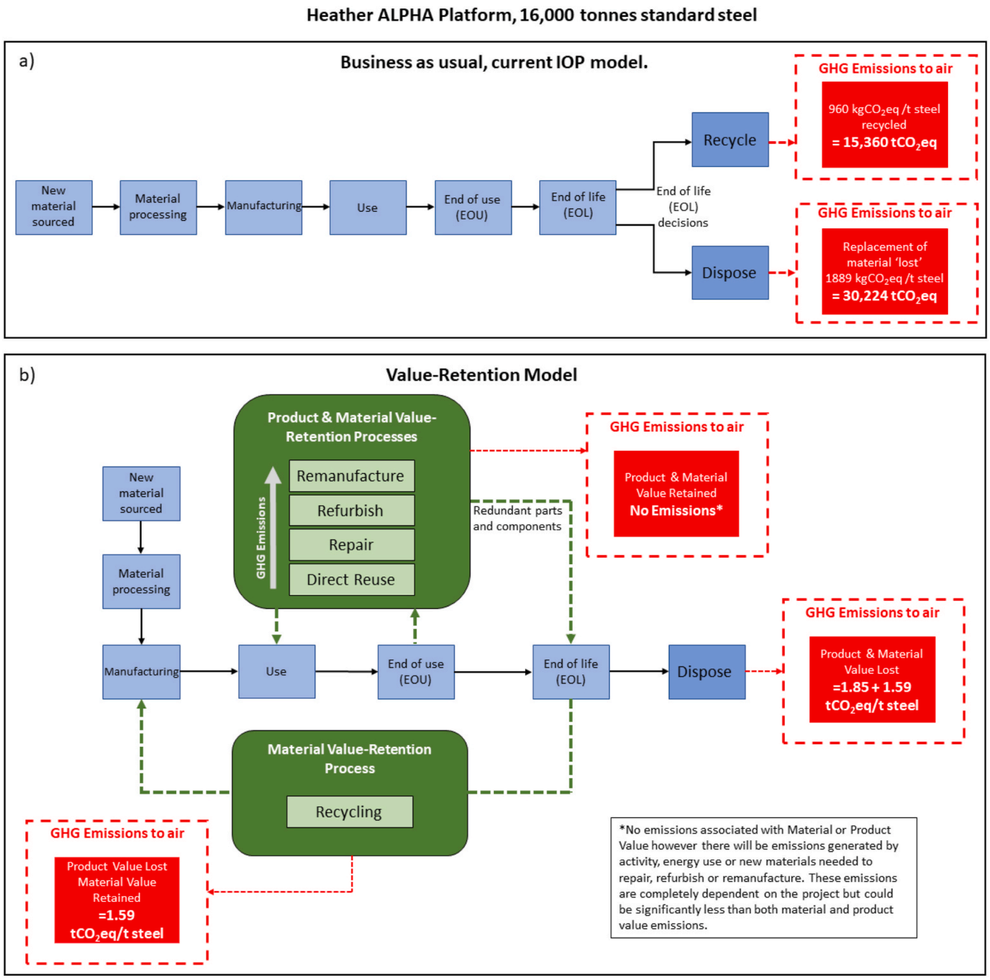

Fig. 13. The steel platform Heather Alpha (weighing 16,000 tonnes of standard steel) used as the example in the IOP guidelines (2000) is also used an example here. Fig. 13a) The current 'business as usual' model based on linear take-make-waste processes. IOP GHG emissions calculations are based on 960kgCO_2 per tonne of steel recycled and a 'replacement' value of 1889kgCO_2 per tonne of steel disposed. Fig. 13b) illustrates the new 'The Value Retention Model' which is based on the UN's IRP VRPs and is presented as a new methodology for calculating GHG emissions in OGI decommissioning. Value Retention Processes (VRP) that distinguish between End of Use (EOU) and End of Life (EOL) scenarios. Based on a Material value of 1.85 tCO_2 per tonne of steel and a Product value of 1.59 tCO2 per tonne of steel. The models do not currently include GHG emissions due to transportation of materials to recycling or disposal points. Adapted from Oakdene Hollins (2020), Nasr et al. (2018) and Hauke et al. (2017).

from decommissioning of oil and gas structures are significantly out of date and are no longer fit for purpose as they leave large sources of GHG emissions unaccounted for and do not include non-recyclable materials in emissions calculations. As it is impossible to directly measure GHG emissions, methods for calculating the volumes need to be consistent and accurate. The IOP guidelines handle end-of-life material management differently depending on the type of material to be managed. GHG emissions due to material endpoints are only calculated for those materials that could be recycled in 2000 and therefore excludes GHG emissions associated with the many materials that are not recyclable, for example many plastics, cement and concrete. Furthermore, no updates have been included which reflect the changing technological landscape of recycling technology which have advanced since the guidelines were written. By ignoring GHG emissions from other non-recycled materials, the IOP guidelines are not following a LCT approach, but in fact picks and chooses where to apply this approach. This gap must be closed as a matter of urgency and all material end-of-life analysis must be applied consistently to the calculations.

The concept of value material and product value within VRPs allows for a mechanism that places the waste hierarchy and circular economy at the heart of GHG emissions calculations, thereby allowing for sensible, logical and realistic GHG emissions figures to be applied to a material's full life cycle (see Figs. 13 and *14*). Furthermore, this model allows a mechanism for accounting for different end of life decisions such as reuse and refurbishment. This model is adaptable and can be applied to other types of steel, other recyclable materials, as well as non-recyclable materials to understand the embedded carbon from both the manufacture of crude materials (such as crude steel) and manufacture of a product from that material.

The model presented allows for a holistic approach that puts design for reuse and design for recycling at the centre of material end-of-life decision making. It simplifies the emissions accounting methods whilst acknowledging that the distinction of primary and secondary materials is not as clear cut as the IOP guidelines allow for. It importantly captures the significant contribution that GHG emissions due to manufacturing a product makes.

Reuse will retrain significant and large volumes of greenhouse gases produced from the manufacture of materials and products, transport and decommissioning operations. The example in Fig. 14 shows that a 16,000 tonne steel structure left in-situ for the purposes of reuse will retain 55,040 tCO_2(eq) of embedded GHG emissions compared to manufacturing a similar structure from new. This figure (Fig. 15) does not include the GHG emissions caused by transporting materials to their end-of-life location (for example recycling centres), nor does it account for GHG emissions caused by operations to remove the structure, both of which could prove significant.

The reuse of structures is key to applying a waste hierarchy approach to decommissioning. This simple LCT philosophy starts with reducing the amount of 'stuff' we use and make, in this case equipment designed for use in the marine environment. By avoiding high energy, materials and emissions costs by reusing components and equipment already in the marine environment, these associated GHG emissions are reduced or 'retained'. Apart from vessel fuel use, this is the single most important way we can deal with waste and reduce overall GHG emissions, allowing the decommissioning industry to respond to the legislative drive to Net Zero Carbon.

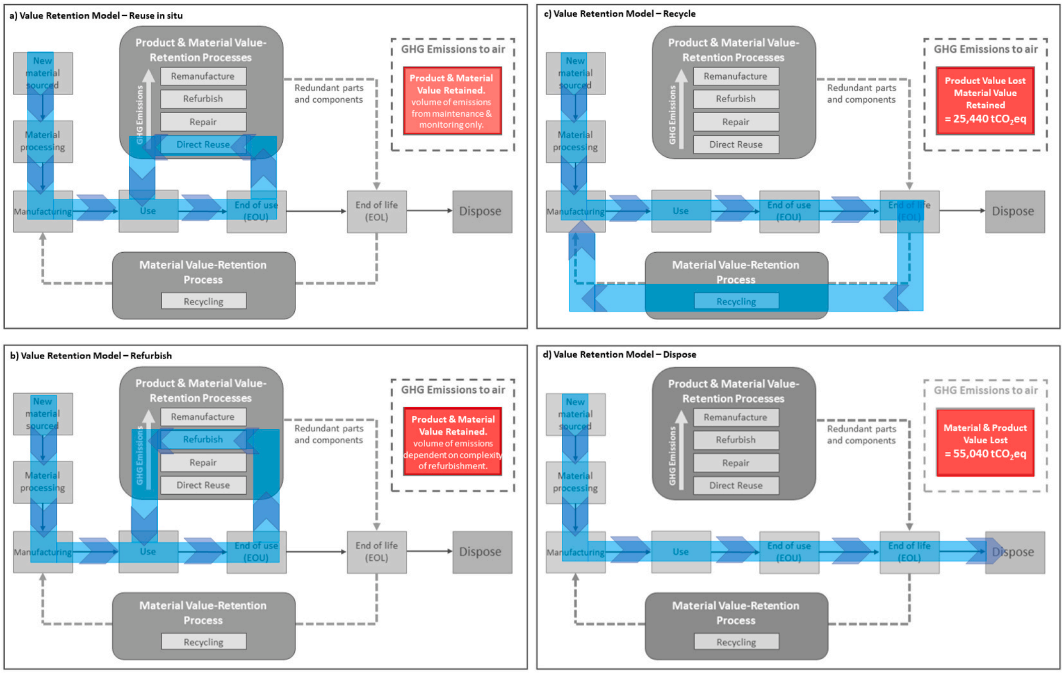

Fig. 14. Value Retention Models for four decommissioning scenarios for the Heather Alpha platform, a 16,000t UK North Sea steel jacket. a) The platform is left in situ for a new purpose such as the base for a wind turbine. Both the material and product values are retained. b) The platform is left in situ with the aim to reuse it after refurbishment. Both material and product value are retained but there will be some GHG emissions associated with the refurbishment operations. c) The steel jacket is entirely removed, and all steel sent for recycling. The product value is lost, but the material value is retained. d) The steel jacket is disposed and consequently both the material value and product value are lost. This scenario is unlikely to happen in the North Sea but may in other geographical settings. Adapted from a combination of Oakdene Hollins (2020), Nasr et al. (2018) and Hauke et al. (2017).

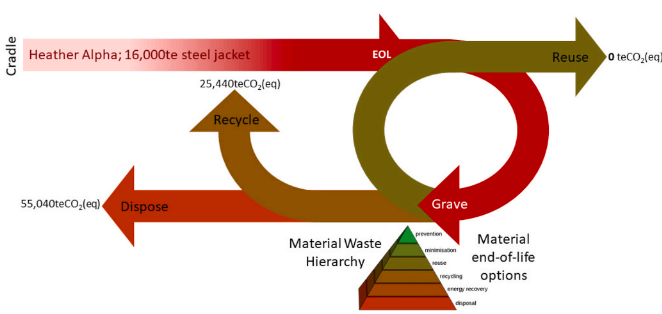

Fig. 15. The circular economy as applied to the Heather Alpha example of a 16,000te steel jacket to be decommissioned. Three options are explored; reuse (leave in situ), recycle all steel and dispose in landfill or at sea. GHG emissions figures for each option are shown on the diagram. No GHG emissions would be calculated with a full reuse option. These figures do not include GHG emissions from decommissioning operations or transport, nor do they include GHG emissions from maintenance and monitoring. Adapted from Nasr et al. (2018).

OSPAR 98/3 and the Brent Spar debate (Bellamy and Wilkinson, 2001) make the reuse of OGI structures controversial in the North Eastern Atlantic Region (including the North Sea). However, the considerable GHG emissions retentions that will be achieved by reuse is a key component on the pathway to Net Zero, and perhaps the only way to reduce emissions to net zero by 2050. Reuse options could include the production of hydrogen, offshore renewables and CCUS to name but a few.

Finally, and significantly, the VR model presented here can be applied at different scales from product to systemic. In the case of OGI decommissioning in the North Sea this could be applied at the steel jacket decommissioning scale (as described here), at decommissioning program scale which involves multiple operations and activities and at a North Sea scale, which would encourage the cooperation between different industries, for example the OGI and the renewable industry and provide a clear systemic path to achieve Net Zero by 2050.

Several assumptions have been made by the authors to enable the quantification of GHG emissions in these decommissioning scenarios. Firstly, the GHG emissions quantified in this study represent a best-case scenario, with no adjustments made for the efficiency of manufacturing, reprocessing or recycling operations.

Secondly, not enough information or data is available to quantify individual GHG emissions per type, so carbon dioxide equivalent figures have been used throughout this study to represent other greenhouse gases such as methane and nitrous oxide.

A gap in the emissions estimates is the deconstruction and reprocessing of steel decommissioned which are often large structures and need to be cut or sawn into smaller more manageable chunks (in terms of both transport and fitting into an EAF). The nature of the cutting equipment is not zero emissions and the number of cuts and the method of cutting will have an impact. This is difficult to quantify, but if the smaller pieces need to be 1–5 tonnes, a 10,000-tonne structure could have between 2000–10,000 cuts.

The data and figures described in this study focusses on standard steel however many products require the manufacturing of specialised steel, for example, low corrosion, high strength steel required in extreme environments such as the marine environment. The embedded carbon associated with these specialised materials needs to be calculated based on the holistic approach presented here and must include both direct emissions sources and indirect emissions sources and all emissions associated with transport.

Although this study has investigated the GHG emissions associated with transporting materials, it has not been possible to simply allocate a GHG emissions figure as there are too many variables and complexities. A complex model identifying all statistically significant variables must be developed which would address this gap.

To allow for technological advances in recycling and material technology the GHG emissions figures presented here should be regularly updated. This is also the case for any changes in the energy mix of the manufacturing country (an increase in renewably generated electricity for example will reduce emissions from burning fossil fuels). Advancements in the manufacturing technologies (for example hydrogen use in crude steel manufacturing) and transport technology (hydrogen or wind powered container ships) will also have an impact and will need to be addressed when the need arises.

Oil and gas operators are very reluctant to share data which could be used as a basis for the development of independent methodologies and models to accurately quantify greenhouse gas emissions from decommissioning activities. This stage of the oil and gas industry is not commercially sensitive however the upstream section of the industry is, and this culture of trade secrets percolates throughout the rest of the industry. The issue of public relations and perception is also significant and can have a cost, commercial and decision-making impact if it goes wrong, the Brent Spar controversy (Bellamy and Wilkinson, 2001) that still lingers on is one such example.

Finally, there is a significant reporting gap that should be addressed; the current practise of calculated GHG emissions that are reported to the local governing body are not compared to the final GHG emissions after operations have been completed, nor is there any statutory reporting requirement to do this. This data would not only allow the accuracy of calculation methods to be analysed, but it would also allow more accurate models, data and methodologies to be designed. Even something as simple as the reporting of actual fuel use during and at the end of the decommissioning program would provide useful data and a relatively easy way to reduce uncertainties in the calculated GHG emissions. 'Lessons learned' is standard practise in OGI exploration and this method of analysing performance could be employed within decommissioning and serve as a basis for 'real time' and 'after operations' GHG emissions reporting to the local governing body, such as BEIS in the UK. This involves a policy change and would require the local governing body to enforce reporting of these 'after operations' GHG emissions calculations.

4. Conclusions and policy implications

The decommissioning of oil and gas structures at the end of their useful life causes large and significant volumes of greenhouse gases to be emitted from the operations, end of life waste management and transport of materials.

The current guidelines for calculating greenhouse gas emissions from decommissioning activities are not fit for purpose. New guidelines and legislation are required to account for all statistically relevant GHG emissions, both before and after decommissioning activities have taken place.

This study shows that direct emissions and indirect emissions make a significant contribution to total GHG emissions calculations and should be included in all GHG emissions studies. Furthermore, this study shows that GHG emissions from marine transport are not well defined, with a huge range of potential emissions calculated here. Further study is urgently needed so that these emissions can be quantified.

To fulfil the Net Zero Carbon agenda, Value Retention Processes developed by the UN's IRP including the concepts of material value and product value allow for a mechanism for reuse, a crucial and key component of the Net Zero strategy. The approach presented here simplifies the emissions accounting methods whilst acknowledging that the distinction of primary and secondary materials is not as clear cut as the IOP guidelines allow for. It captures the significant contribution that GHG emissions due to manufacturing a product can make, a gap in the original guidelines.

A Net Zero Carbon approach to quantifying GHG emissions allows a more complete understanding of GHG emission sources, allowing for the development of true to reality, baseline GHG emissions, from which a quantified reduction strategy can be developed. Furthermore, this approach would allow decommissioning to be placed within a circular economy and waste hierarchy context, important methods for realising GHG emissions reductions.

The methods and VR model presented here are easily transferable and can be applied to other industries, including renewable and nuclear decommissioning as well as being placed in a wider geographical context.

The VR model works at all scales from product to systemic and can be placed within wider sustainable business and economic models.

Author contributions

A.J.D. led the writing, conceptualization of ideas and designed the methodology with contributions from A.H. A.J.D. gathered the data for analysis. All authors contributed to the drafting and revision of the article and gave approval of the final version of this manuscript before submission.

CRediT authorship contribution statement

Abigail J. Davies: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Visualization. **Astley Hastings:** Writing – review & editing, Supervision, data validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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