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Bottom-up emissions and energy assessment for decommissioning offshore platform structures in the North Sea: Brent and Tern case studies

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ABSTRACT

Decommissioning of offshore energy infrastructure in the North Sea presents a significant environmental challenge for operators, the supply chain, government agencies, and society. Considering the UK's 2050 net zero target, it is essential to understand the offshore oil and gas (O&G) decommissioning sector's contribution to overall emissions. Such insight is crucial for evaluating decommissioning projects and informing policy development aimed at reducing emissions and achieving net zero goals. This study proposes a bottom-up emissions and energy assessment (EEA) approach for decommissioning offshore O&G platform topside and jacket structures. The approach quantifies the greenhouse gas (GHG) emissions and energy demand associated with offshore and onshore activities during the decommissioning phase. It leverages detailed, site-specific operational data to improve the precision and reliability of these assessments and is underpinned by the latest available data from the North Sea O&G decommissioning industry. The approach is validated through application to decommissioning of platform topsides and jackets in the Brent and Tern fields. Numerical comparisons reveal acceptable differences between the energy demand and CO_2 emission estimates from this study and those reported in North Sea industry reports. The study also presents insights into the reliable EEA of decommissioning projects.

1. Introduction

The decommissioning of large-scale offshore oil and gas (O&G) infrastructure in the North Sea presents significant economic and environmental challenges that operators, the supply chain, regulators, and society need to manage (Burdon et al., 2018; Sommer et al., 2019). It is estimated that half of the O&G fields in the UK continental shelf (UKCS) (Offshore Energy UK (OEUK), 2023) have already reached or are approaching the end of their operational lifetimes, and their infrastructure should be removed from the seabed based on the Convention for the Protection of the Marine Environment of the North-East Atlantic, or OSPAR (OSPAR Commission, 1998), with limited exceptions. Current cost estimations highlight the economic scale of decommissioning projects, with the North Sea Transition Authority (NSTA) (2023) reporting that the O&G industry spent approximately £8 billion on the decommissioning of O&G wells and infrastructure between 2017 and 2022. This is anticipated to reach £40 billion by 2050. However, the potential environmental impacts of O&G decommissioning projects are still not well understood worldwide (Sommer et al., 2019; Reda et al., 2025).

From an environmental viewpoint, the global O&G industry faces a dilemma when deciding whether infrastructure should be removed entirely from the seabed or whether some components can be left in place as they are (Fowler et al., 2014; Reda et al., 2023; Reda et al., 2024). Over their lifetimes, O&G platforms provide important habitats

Abbreviations: AHV, Anchor Handling Vessel; BV, Barge Vessel; CA, Comparative Assessment; CSV, Construction Support Vessel; DP, Decommissioning Programme; DWC, Diamond Wire Cutting; DSV, Diving Support Vessel; EEA, Emissions and Energy Assessment; EIA, Environmental Impact Assessment; GHG, Greenhouse Gas; HLV, Heavy Lift Vessel; IoP, Institute of Petroleum; IMO, International Maritime Organisation; ICE, Inventory of Carbon and Energy; LAT, Lowest Astronomical Tide; NSTA, North Sea Transition Authority; OPRED, Offshore Petroleum Regulator for Environment and Decommissioning; OSV, Offshore Support Vessel; O&G, Oil and Gas; OSPAR, Oslo and Paris Conventions; ROV, Remotely Operated Vehicle; ROVSV, ROV Support Vessel; SLV, Single Lift Vessel; SBV, StandBy Vessel; TD, Technical Document; TB, Tug Boat; UKCS, UK Continental Shelf; WoW, Wait on Weather.

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for different marine species, including apex predators such as marine mammals (Bell and Smith, 1999; Todd et al., 2009). This has been highlighted by a range of experts as a potential reason for relaxing complete removal policies and keeping some O&G infrastructure in place to preserve the species biodiversity (Sommer et al., 2019; Fowler et al., 2020; Coolen et al., 2020). Furthermore, the O&G decommissioning projects include a set of large-scale offshore and onshore engineering operations performed by different fuel-intensive vessels and equipment with significant greenhouse gas (GHG) emissions (Sommer et al., 2019). Considering the UK's 2050 net zero target (Department for Energy Security and Net Zero, 2019), it is important to understand the O&G decommissioning sector's contribution to overall emissions. This understanding is essential for evaluating decommissioning scenarios, developing effective policies to support emission reductions, and meeting net zero emissions targets. This study focuses on quantifying GHG emissions and energy demand associated with offshore and onshore operations, as part of assessing certain aspects of the environmental impact assessment (EIA) of O&G decommissioning projects.

Recent literature review by Tan et al. (2021) reveals that current quantitative estimation methods for EIA only consider limited activities in O&G decommissioning. As Watson et al. (2023) state in their review, the boundaries of quantification approaches should include the environmental footprint of all stages of decommissioning scenarios, from offshore operations to onshore material dismantling, disposal, transportation, and recycling. However, the quantification of GHG emissions and energy demand for the various offshore and onshore decommissioning operations and activities is not straightforward. For example, the lack of field-specific data, technological changes, incomplete fuel consumption data for vessels and equipment, uncertainties in decommissioning and onshore waste management scenarios, unknown post-removal material flows, and weather-related vessel delays all present challenges in the development of accurate emissions and energy estimation approaches.

The quantification of emissions and energy demand is an integral part of the EIA of O&G decommissioning. Recent reviews by Watson et al. (2023) and Tan et al. (2021) highlight the absence of standard methodologies for this purpose. They emphasise that robust approaches should systematically identify and account for all relevant emissions and energy sources, incorporate local data, and reflect national and international regulatory requirements. Consequently, the development of transparent, standardised methods for emissions and energy demand quantification in O&G decommissioning remains a critical gap in the current literature. In particular, more granular, bottom-up approaches are expected to yield not only more holistic, project-specific estimates but also to improve public understanding and transparency regarding the emissions and energy demand associated with decommissioning activities. This has recently led to the development of a bottom-up emissions and energy demand model for O&G pipelines by Jalili et al. (2024a). Considering this research gap, additional bottom-up models are required for the decommissioning of other O&G assets, including platform topsides, jackets, wells, and subsea structures. This study proposes a bottom-up emissions and energy demand estimation approach for the decommissioning of platform topsides and jackets.

In the development of quantitative emissions and energy demand estimation models, a bottom-up approach is key (Jalili et al., 2024a; Huang et al., 2024; Arioli et al., 2020). Bottom-up approaches estimate the emissions, energy demand, or costs by considering detailed decommissioning operations and related local data, vessel and equipment types, transportation strategies, material waste management scenarios, and so on. In contrast to the top-down approach, in which given percentages are used to estimate the cost and emissions of a given decommissioning operation (Milne et al., 2021; Jalili et al., 2024b), this methodology can provide more accurate figures for the GHG emissions and energy footprints of decommissioning activities. However, the development of a reliable bottom-up approach for O&G decommissioning projects requires solid assumptions for the input data, which can be difficult to acquire in the O&G industry (Murray et al., 2018). Currently available local data sets for emissions and energy demand factors are either outdated or not available. For example, the guidance published by the Institute of Petroleum (IoP) (2000) provides the emissions factors and energy demand dataset for the different vessels and equipment types. However, this dataset may have changed over time following the technological progress. Moreover, the offshore and onshore decommissioning activities may vary from one project to another, which makes it harder to develop a general model for energy demand and emissions estimation.

This study seeks to develop an emissions and energy assessment (EEA) approach for the decommissioning of offshore O&G platform topsides and jacket structures, with a particular focus on enhancing boundary comprehensiveness and improving the accuracy of energy demand and emissions quantification. The overall framework of the proposed EEA approach is illustrated in Fig. 1. The proposed EEA approach captures the environmental footprint of a broad range of offshore and onshore activities undertaken during the decommissioning phase. It employs a bottom-up methodology, utilising site-specific and detailed operational data to enhance the accuracy and robustness of energy consumption and emissions quantification. Particular attention is given to the identification of key influencing parameters across both offshore and onshore processes. The bottom-up model is informed by the most recent and relevant data from the North Sea O&G decommissioning sector (Shell UK, 2017a; TAQA, 2024; Hammond et al., 2011a; ConocoPhillips, 2018; Institute of Petroleum (IoP), 2000). The effectiveness of the proposed approach is validated through its application to two decommissioning case studies in the North Sea: the topside platform and jacket structures of the Brent and Tern fields. Comparative analysis against available industry data highlights the capability of the bottom-up methodology to provide holistic estimates of GHG emissions and energy demand.

2. Decommissioning

In this section, the expected activities and operations involved in the decommissioning of platform topside and jacket structures are presented.

2.1. Platform topside decommissioning

Based on the current decommissioning practice in the North Sea, different scenarios can be applied for platform topside removal, such as reverse installation, piece-small, and single lift (CNR International, 2013a; TAQA, 2021; da Cunha Jácome Vidal et al., 2022). As its name suggests, the reverse installation scenario involves multiple lifting operations of topside modules in the reverse order of operations carried out during the installation and is normally performed by a heavy lift vessel (HLV). In the piece-small scenario, the topside undergoes a set of offshore deconstruction operations to disconnect and then cut up the topside modules. The resulting parts are then lifted individually or in a set of component groups to a barge vessel (BV) or a supply vessel for transport to shore. Both reverse installation and piece-small scenarios demand significant effort for the offshore preparation of various modules. These scenarios are not ideal from cost and safety viewpoints due to the need for long-term offshore vessel operations as well as the risks of offshore deconstruction and multiple lifts for offshore personnel.

The single lift is the most efficient, fast, and reliable scenario for platform topside removal. Experience from decommissioning in the North Sea, involving the lifting and transport of large platform topsides ($>$ 20,000 t) to shore, highlights the success and reliability of this scenario (Shell, 2026). Large single lift vessels (SLVs) operating on dynamic positioning, such as Pioneering Spirit (Allseas, 2026), can rapidly lift platform topsides, for example, the Brent Delta platform was lifted by Pioneering Spirit in 10 s (Shell, 2026). In the single lift scenario, the lift is carried out by lifting beams with dynamic lifting jacks. As the SLVs are

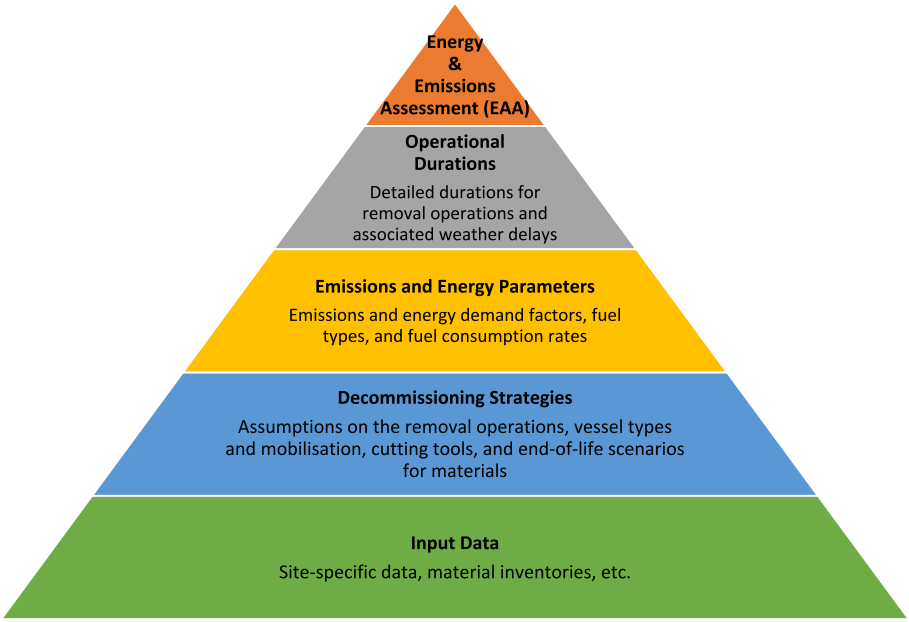


Fig. 1. Overall framework of the proposed emissions and energy assessment (EEA) approach for the decommissioning of offshore O&G platform topsides and jacket structures.

Table 1
The list of offshore operations and employed vessels for the platform topside removal.

Operations	Details	Notation	Vessel/equipment
Topside lift	Lifting the platform topside in a single lift	O_0	Single lift vessel (SLV)
Cargo	Transferring the topside to a barge vessel (BV) and shipping to the shore	O_1	Barge vessel (BV)
Towing	Towing the BV using a tug boat (TB)	O_2	Tug boat (TB)
Harbour activities	Anchor handling vessel (AHV) with a TB for assisting the topside offloading from the BV	O_3	Anchor handling vessel (AHV) or offshore support vessel (OSV), Tug boat (TB)
Guard operation	Guarding the offshore operations using a standby vessel (SBV)	O_4	Standby vessel (SBV)

usually not capable of operating in near-shore shallow waters, the topside is often transferred to a BV for transport to onshore dismantling facilities. Hence, the topside is shipped by the SLV to a near-shore load transfer location and then placed on the BV. Thereafter, the BV is towed by tug boats (TBs) to shore for offloading the topside. The topside is dismantled at an onshore dismantling and processing facility. Depending on the project, the dismantled components are then transported to the recycling centres using road, rail, barge, or bulk carrier transport modes. A list of the offshore operations and corresponding vessel utilisation for an O&G platform topside removal campaign is provided in Table 1.

2.2. Jacket decommissioning

Most O&G platform foundations are steel jacket structures (Fu, 2018). For some large platforms, such as Brent Alpha (Shell UK, 2017), the weight of the jacket structure can exceed 30,000 t including the footings and piles driven into the seabed. Based on the currently available decommissioning programmes in the North Sea, full and partial removal are the two options for jacket decommissioning. In the full removal option, the jacket including its footings is lifted and transported to shore for recycling and disposal. However, the scale of the lifting operation and the removal of piles driven into the seabed create serious technical, safety, and environmental challenges. With the partial removal option, the jacket is cut and removed from the top of the footings (The British Petroleum (BP), 2011). OSPAR Decision 98/3 (1998) and the UK Offshore Petroleum Regulator for Environment and Decommissioning (OPRED) recognise that the full removal of jackets weighing more than 10,000 t in air can be difficult.

Due to the difficulty of complete removal of jacket footings driven into the seabed, a partial removal approach is often adopted, with the remaining footings proposed for derogation. Based on OSPAR Decision 98/3, the footings of a jacket structure are defined as "*all that part of a steel installation which is below the highest point of the piles which connect the installation to the seabed*" (OSPAR Commission, 1998). The OPRED guidance (2018) notes that potential derogation cases are considered individually for jackets weighing more than 10,000 t in air, to determine whether it may be appropriate to leave the footings of such large steel jacket structures in place. Therefore, current practice in the North Sea decommissioning sector shows that O&G operators are increasingly willing to make a derogation case, in line with OSPAR and OPRED requirements, for the remaining jacket footings on the seabed and to partially remove the jacket.

The cutting line of the jacket depends on the specifics of the project. For example, the Miller decommissioning programme (DP) (BP, 2011) assumes that the jacket will be partially removed from approximately 80 m below sea level. The subsea cutting process was performed using a diamond wire cutting (DWC) tool supported by a remotely operated vehicle (ROV), while alternative cutting tools were used for cutting the smaller structural elements (Shell UK, 2017).

In the partial jacket removal option, two main scenarios are typically considered: refloat and single lift.[1] Since most jacket structures were originally installed using the floating method through controlled ballasting, the refloat method essentially reverses the installation process.

[1] Note: Piece small was used on BP North West Hutton due to structural issues which precluded single lift (British Petroleum (BP), 2005).

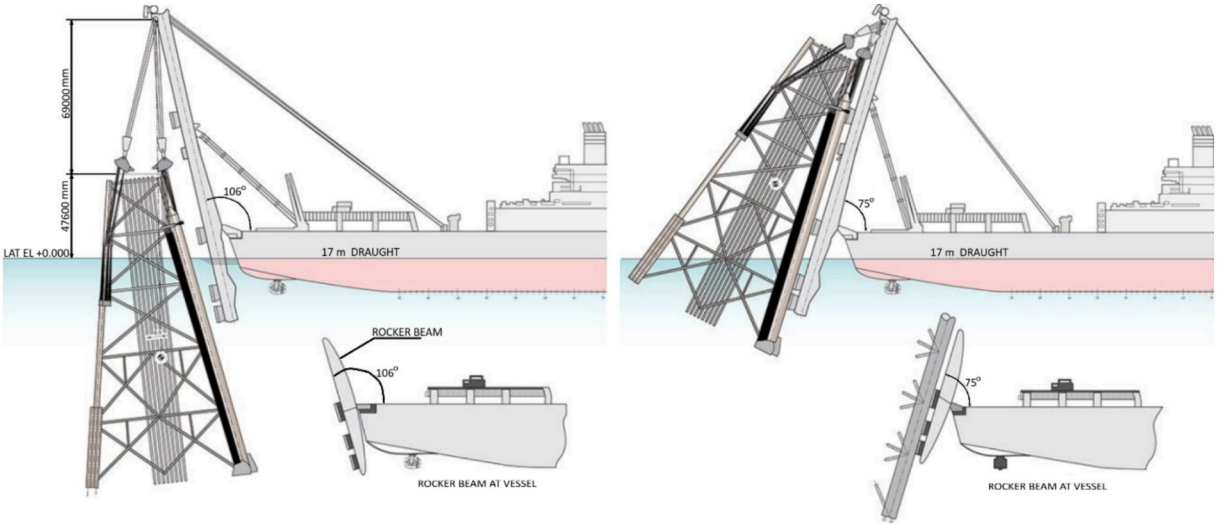


Fig. 2. Lifting operation of Brent Alpha jacket structure using SLV (Shell UK, 2017b).

In this approach, the jacket is re-floated using its inherent buoyancy, supplemented by additional buoyancy tanks attached to the structure. These tanks are necessary because the jacket becomes heavier over its operational lifetime due to added structural components, and because many of the members that originally provided buoyancy during installation are now flooded. Brent Alpha (Shell UK, 2017), Brae Bravo (TAQA, 2022), Indefatigable Juliet-D, Juliet-P, Kilo, Lima, Mike, and November (Shell UK, 2014), and Murchison (CNR International, 2013b; CNR International, 2014) are examples of DPs that considered the refloat & tow scenario. In the single lift scenario, the whole upper jacket section is removed in a single lift using an SLV. The single-lift method is generally preferred, primarily due to the technical challenges and limited industry experience associated with refloat and tow operations using buoyancy tanks (Shell UK, 2017). Therefore, the focus of this study is on the single lift jacket removal scenario.

In the single lift scenario, the conductors are first cut by a DWC tool deployed by ROV from an HLV, or a diving support vessel (DSV), or a construction support vessel (CSV). Then, the structural elements of the jacket are cut at a given depth above the seabed by the DWC tool operated by a ROV from a ROV support vessel (ROVSV). During the cutting operation, the crane lifting strops are attached to the lifting points on the jacket, as shown in Fig. 2 (Shell UK, 2017b). Once the final cuts are completed, the jacket structure is lifted and, in the case of Pioneering Spirit, rotated back by SLV using the specifically designed tilting lifting beam (Shell UK, 2017b). Thereafter, the removed jacket structure may be shipped directly to a deep-water port or shipped to a near-shore site for transfer to a BV. In the latter case, the BV, supported by TBs, receives the jacket to ship and offload it at an onshore location. Considering these steps, the offshore operations, required vessels, and equipment for jacket removal in the single-lift scenario are summarised in Table 2.

3. Proposed bottom-up EEA approach

This section presents the system boundary of the proposed approach and provides the bottom-up EEA formulations developed for the decommissioning of platform topsides and jacket structures. Without loss of generality, the formulations are applicable to the emissions and energy demand estimation for both platform topside and jacket structures. The formulations consider various parameters to calculate the emissions and energy demand for the different operations and activities involved in removal campaigns. Readers are referred to Appendix A for the definitions and units for the various parameter categories used in this section.

3.1. System boundary

The system boundary plays a key role in the reliability of any EEA approach. The more comprehensive the system boundary is, the more holistic the resulting emissions and energy demand estimates are expected to be. However, predicting and including all emissions and energy demand sources is not always possible due to data gaps and uncertainties in activities.

Fig. 3 illustrates the system boundary of the proposed EEA approach, which includes major offshore removal vessel operations and onshore operations. Due to a lack of data, the emissions and energy demand associated with offshore platform and jacket preparation operations, fuel delivery for vessels, and consumable materials are not considered in this study. However, it is expected that the proposed bottom-up EEA approach provides relatively holistic emissions and energy demand estimates by considering the major offshore and onshore activities.

Table 2
The list of operations alongside of employed vessels and equipment for the jacket upper section removal.

Operations	Details	Notation	Vessel/equipment
Conductor cutting	Cutting the conductors in the upper section of the jacket	O_0	High lift vessel (HLV)
Jacket cutting	Cutting jacket elements	O_1	Remotely operated vehicle support vessel (ROVSV)
Upper jacket lift	Lifting the upper jacket and placing it on the BV's deck space	O_2	Single lift vessel (SLV)
Transportation	Shipping the upper jacket to shore using BV towed by a TB	O_3	Barge vessel (BV), tug boat (TB)

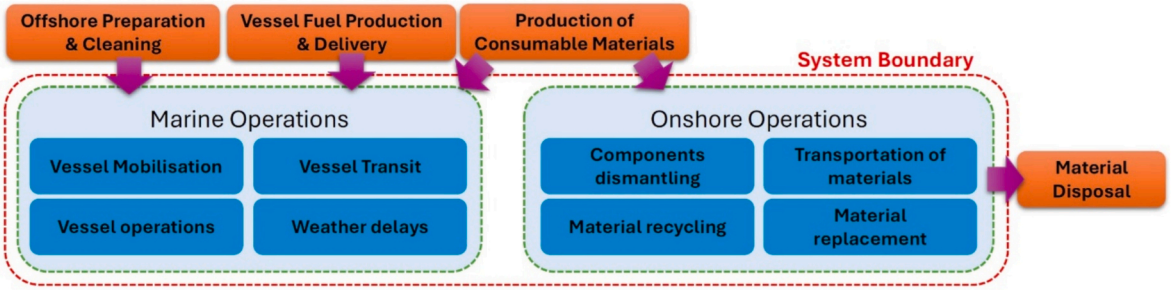


Fig. 3. The system boundary for the emissions and energy assessment (EEA) of platform and jacket decommissioning.

3.2. Energy demand

The total energy demand during the decommissioning campaign results from a series of offshore and onshore operations and can be expressed as:

$$E = E^{\text{off}} + E^{\text{on}} \tag{1}$$

in which the energy demand for offshore operations, E^{off}, is obtained by considering the type of vessels and equipment, fuel consumption rates, operational durations, and energy factors as:

$$E^{\text{off}} = \sum_{i=1}^{N} \sum_{j=0}^{n_i-1} e_i f_j \tag{2}$$

where e_j represents the energy content of the fuel consumed in the jth operation. The fuel consumptions, f_j, are different for the topside and jacket removals. Here, the fuel consumptions associated with the topside removal are denoted by f_j^{T}, while the corresponding values for the jacket is indicated by f_j^{J}. To calculate the energy demand for topside or jacket removal, the parameter f_j in Eq. (2) needs to be replaced by f_j^{T} or f_j^{J}. The fuel consumptions associated with the topside and jacket removal operations are obtained as follows:

- Platform topside structure removal:

$$f_0^{\text{T}} = f_{\text{m}}^{\text{SLV}} t_{\text{m,T}}^{\text{SLV}} + f_{\text{tr}}^{\text{SLV}} t_{\text{tr,T}}^{\text{SLV}} + (1+\alpha_0) f_{\text{o}}^{\text{SLV}} t_{\text{o,T}}^{\text{SLV}} \tag{3}$$

$$f_1^{\text{T}} = 0 \tag{4}$$

$$f_2^{\text{T}} = f_{\text{m}}^{\text{TB}} t_{\text{m,T}}^{\text{TB}} + f_{\text{tr}}^{\text{TB}} t_{\text{tr,T}}^{\text{TB}} + (1+\alpha_1) f_{\text{o}}^{\text{TB}} t_{\text{o,T}}^{\text{TB}} \tag{5}$$

$$f_3^{\text{T}} = f_{\text{m}}^{\text{AHV}} t_{\text{m,T}}^{\text{AHV}} + f_{\text{tr}}^{\text{AHV}} t_{\text{tr,T}}^{\text{AHV}} + (1+\alpha_2) f_{\text{o}}^{\text{AHV}} t_{\text{o,T}}^{\text{AHV}} \tag{6}$$

$$f_4^{\text{T}} = f_{\text{m}}^{\text{SBV}} t_{\text{m,T}}^{\text{SBV}} + f_{\text{tr}}^{\text{SBV}} t_{\text{tr,T}}^{\text{SBV}} + (1+\alpha_3) f_{\text{o}}^{\text{SBV}} t_{\text{o,T}}^{\text{SBV}} \tag{7}$$

- Jacket structure removal:

$$f_0^{\text{J}} = f_{\text{m}}^{\text{HLV}} t_{\text{m,J}}^{\text{HLV}} + f_{\text{tr}}^{\text{HLV}} t_{\text{tr,J}}^{\text{HLV}} + (1+\alpha_0) f_{\text{o}}^{\text{HLV}} t_{\text{o,J}}^{\text{HLV}} \tag{8}$$

$$f_1^{\text{J}} = f_{\text{m}}^{\text{ROVSV}} t_{\text{m,J}}^{\text{ROVSV}} + f_{\text{tr}}^{\text{ROVSV}} t_{\text{tr,J}}^{\text{ROVSV}} + (1+\alpha_1) f_{\text{o}}^{\text{ROVSV}} t_{\text{o,J}}^{\text{ROVSV}} \tag{9}$$

$$f_2^{\text{J}} = f_{\text{m}}^{\text{SLV}} t_{\text{m,J}}^{\text{SLV}} + f_{\text{tr}}^{\text{SLV}} t_{\text{tr,J}}^{\text{SLV}} + (1+\alpha_2) f_{\text{o}}^{\text{SLV}} t_{\text{o,J}}^{\text{SLV}} \tag{10}$$

$$f_3^{\text{J}} = f_{\text{m}}^{\text{TB}} t_{\text{m,J}}^{\text{TB}} + f_{\text{tr}}^{\text{TB}} t_{\text{tr,J}}^{\text{TB}} + (1+\alpha_3) f_{\text{o}}^{\text{TB}} t_{\text{o,J}}^{\text{TB}} \tag{11}$$

It should be noted that $0 \le \alpha_i \le 1$ in the above equations represents the wait on weather (WoW) parameters that account for operational delays in the field due to the weather conditions. The WoW parameters are only applied to the vessels in operational mode.

The energy demand of onshore operations, E^{on}, in eq. (1) depends on how materials are dismantled, processed, transported, and recycled onshore. Thus, the energy demand of onshore operations, E^{on}, can be written as:

$$E^{\text{on}} = E^{\text{odp}} + E^{\text{otr}} + E^{\text{rp}} \tag{12}$$

in which the energy demand from onshore dismantling, processing, transport, and recycling can be estimated based on the material weights,

Table 3
Fuel consumption rates for the different operational modes of vessels involved in platforms topsides and jacket removals (tonne/day).

Vessels	Mobilisation/De-mobilisation		In transit		In field/operation		WoW		Fuel type
	Notation	Value	Notation	Value	Notation	Value	Notation	Value	
Single lift vessel (SLV)	$f_{\text{m}}^{\text{SLV}}$	25[a]	$f_{\text{tr}}^{\text{SLV}}$	300[d]	$f_{\text{o}}^{\text{SLV}}$	70 (Offshore Engineer, 2017)	$f_{\text{w}}^{\text{SLV}}$	12[a]	Low speed vessel (heavy oil)
Heavy lift vessel (HLV)	$f_{\text{m}}^{\text{HLV}}$	10[c] (Fairfield Energy, 2021)	$f_{\text{tr}}^{\text{HLV}}$	50 (Fairfield Energy, 2021)	$f_{\text{o}}^{\text{HLV}}$	20 (Fairfield Energy, 2021)	$f_{\text{w}}^{\text{HLV}}$	25 (Fairfield Energy, 2021)	Low speed vessel (marine diesel oil)
Tug boat (TB)	f_{m}^{TB}	2 (Fairfield Energy, 2021)	$f_{\text{tr}}^{\text{TB}}$	50 (Fairfield Energy, 2021)	f_{o}^{TB}	30 (Fairfield Energy, 2021)	f_{w}^{TB}	15 (Fairfield Energy, 2021)	Medium speed vessel (marine diesel oil)
Anchor handling vessel (AHV)[b]	$f_{\text{m}}^{\text{AHV}}$	2 (Institute of Petroleum (IoP), 2000)	$f_{\text{tr}}^{\text{AHV}}$	28 (IoP, 2000)	$f_{\text{o}}^{\text{AHV}}$	25 (IoP, 2000)	$f_{\text{w}}^{\text{AHV}}$	25 (IoP, 2000)	Medium speed vessel (marine diesel oil)
Standby vessel (SBV)	$f_{\text{m}}^{\text{SBV}}$	0.2 (IoP, 2000)	$f_{\text{tr}}^{\text{SBV}}$	3.5 (IoP, 2000)	$f_{\text{o}}^{\text{SBV}}$	1 (Ithaca Energy (UK) limited, 2021)	$f_{\text{w}}^{\text{SBV}}$	3.5 (IoP, 2000)	Medium speed vessel (marine diesel oil)
ROV support vessel (ROVSV)	$f_{\text{m}}^{\text{ROVSV}}$	2 (CNR International, 2013a)	$f_{\text{tr}}^{\text{ROVSV}}$	15 (Fairfield Energy, 2021)	$f_{\text{o}}^{\text{ROVSV}}$	30 (Fairfield Energy, 2021)	$f_{\text{w}}^{\text{ROVSV}}$	5 (CNR International, 2013a)	Medium speed vessel (marine diesel oil)

[a] Assumed in this study.
[b] Due to absence of data, usual OSV fuel consumptions are considered.
[c] Due to absence of data, the mobilisation fuel consumptions of the HLV with dynamic positioning-type is assumed same as for other HLV types.
[d] Based on the sources from industry.

Table 4
Emission ε_f and energy e_f factors for different fuel types.

Parameters	Energy content (GJ/t)	Emissions (tonne emitted/t fuel)		
		CO_2	NO_X	SO_2
Medium speed vessel with marine diesel oil	45.40 (Institute of Petroleum (IoP), 2000)	3.17 (IoP, 2000)	0.059 (IoP, 2000)	$20 \times S \times {}^{10-3}$ [a] (IoP, 2000)
Low speed vessel with heavy oil	40.60 (IoP, 2000)	3.20 (IoP, 2000)	0.084 (IoP, 2000)	$20 \times S \times {}^{10-3}$ [a] (IoP, 2000)
Low speed vessel with marine diesel oil	45.40 (IoP, 2000)	3.20 (IoP, 2000)	0.084 (IoP, 2000)	$20 \times S \times {}^{10-3}$ [a] (IoP, 2000)

[a] S = Sulphur content of the fuel, which is considered as 10% in line with International Maritime Organisation (IMO)(2018).

using a set of energy demand factors as:

$$E^{odp} = e^{odp} \sum_{i=0}^{n_m-1} w_i \tag{13}$$

$$E^{otr} = e^{otr} D \sum_{i=0}^{n_m-1} w_i \tag{14}$$

$$E^{rp} = \sum_{i=0}^{n_m-1} \left(e_i^r + (1-\beta_i) e_i^p\right) w_i \tag{15}$$

Note that the parameter w_i indicates the mass of the ith material in the topside or jacket structures.

3.3. Emissions

Similarly, the emissions caused by the topside removal operations can be seen as result of offshore and onshore activities, expressed as:

$$\mathfrak{E} = \mathfrak{E}^{off} + \mathfrak{E}^{on} \tag{16}$$

where the emissions produced by the offshore operations, $\mathfrak{E}^{off}$, is obtained by considering the fuel consumptions and emissions factors, as:

$$\mathfrak{E}^{off} = \sum_{i=0}^{n_i-1} \varepsilon_j f_j \tag{17}$$

where the fuel consumption parameters f_j needs to be replaced by f_j^T or f_j^J obtained from eqs. (3–11) for the topside and jacket, respectively,.

The emissions resulted from the onshore activities, $\mathfrak{E}^{on}$, can be expressed as:

$$\mathfrak{E}^{on} = \mathfrak{E}^{odp} + \mathfrak{E}^{otr} + \mathfrak{E}^{rp} \tag{18}$$

in which the emissions caused by the onshore dismantling, processing, transport, recycling, and reproduction can be calculated by considering the weight of the materials, fuel consumption, and appropriate emissions factors, as:

$$\mathfrak{E}^{odp} = \varepsilon^{odp} \sum_{i=0}^{n_m-1} w_i \tag{19}$$

$$\mathfrak{E}^{otr} = f^{otr} \varepsilon^{otr} \sum_{i=0}^{n_m-1} w_i \tag{20}$$

$$\mathfrak{E}^{rp} = \sum_{i=0}^{n_m-1} \left(\varepsilon_i^r + (1-\beta_i) \varepsilon_i^p\right) w_i \tag{21}$$

where the corresponding material masses w_i in topsides and jacket need to be replaced when calculating the emissions for the onshore activities.

As can be seen from the bottom-up formulations presented in Sections 3.2 and 3.3, the energy demand and emissions are functions of a set of operational parameters. The values for these parameters are discussed in Section 4.

4. Data mapping

The bottom-up formulations in Section 3 rely on parameters such as activity durations, emission factors, fuel consumption rates, energy demand factors, distances, and WoW parameters, which must be selected carefully to achieve realistic energy demand and emissions estimates. To address uncertainties and data limitations, sources from the North Sea O&G decommissioning sector (DPs, environmental statements, technical reports, guidelines, and references) have been reviewed, and appropriate parameter values have been adopted. Where data were unavailable, best-available estimates are provided in this study.

The fuel consumption, emission, and energy demand parameters in

Table 5
The possible values for the energy demand, fuel consumption, emission, and distance parameters associated with the onshore dismantling, processing, and transport operations.

Parameter	Notation	Unit	Value	Comments
Energy demand by the onshore dismantling and processing	e^{odp}	GJ/t removed material	0.56 (Institute of Petroleum (IoP), 2000)	
Energy demand from the transport of materials from onshore dismantled materials per distance	e^{otr}	GJ/ t material /km	0.00029 (IoP, 2000)	Train transport of scrap material is assumed.
Distance from onshore site to the recycling site	D	km	850 (Moltu and Aavik, 2010)	Average distance for North Sea decommissioning projects reported by Moltu and Aavik (Moltu and Aavik, 2010) is assumed.
Emissions caused by the onshore dismantling and processing	ε^{odp}	tonne emitted/t material	$CO_2 = 0.0368$ $NO_X = 0.0007$ $SO_2 = 0.0001$	Assumed based on IoP (IoP, 2000)
Fuel consumed by onshore transport of removed materials to the recycling facility	f^{otr}	tonne fuel/t material	0.0057 (Moltu and Aavik, 2010)	Moltu and Aavik (Moltu and Aavik, 2010) reported fuel consumption of 19 t for 3315 t of removed materials, i.e., 19/3315 = 0.0057 t of diesel fuel/t of removed materials.
Emission factors for the onshore transport	ε^{otr}	tonne emitted /tonne of fuel	$CO_2 = 3.17$ $NO_X = 0.059$ $SO_2 = 0.01$	Assumed based on rail transport from IoP (IoP, 2000)

Table 6
The energy demand e_i^{rp} and emissions ε_i^{rp} from recycling and manufacturing of various materials.

Material	Recycling				Manufacturing			
	Energy demand (GJ/ t)	Emissions (tonne emitted /tonne)			Energy demand	Emissions (tonne emitted /tonne)		
		CO_2	NO_X	SO_2		CO_2	NO_X	SO_2
Standard Steel	9.40 (Hammond et al., 2011c)	0.44 (Hammond et al., 2011c)	0.0016 (Institute of Petroleum (IoP), 2000)	0.0038 (IoP, 2000)	35.40 (Hammond et al., 2011c)	2.71 (Hammond et al., 2011c)	0.0035 (IoP, 2000)	0.0055 (IoP, 2000)
High Alloyed Steel (includes stainless steel)	9.00 (IoP, 2000)	0.44 (Hammond et al., 2011c)	0.0016 (IoP, 2000)	0.0038 (IoP, 2000)	56.00 (IoP, 2000)	6.15 (Hammond et al., 2011c)	0.0059 (IoP, 2000)	0.2730 (IoP, 2000)
Aluminium	29.00 (Li et al., 2023)	1.69 (Hammond et al., 2011c)	0.0013 (IoP, 2000)	0.017 (IoP, 2000)	218.00 (Hammond et al., 2011c)	11.46 (Hammond et al., 2011c)	0.0041 (IoP, 2000)	0.0249 (IoP, 2000)
Copper	50 (Hammond et al., 2011a)	3.1 (Hammond et al., 2011c)	N/A[d]	0.1200 (IoP, 2000)	100.00 (IoP, 2000)	7.175 (IoP, 2000)	0.0200 (IoP, 2000)	0.2000 (IoP, 2000)
Zinc	9.00 (Hammond et al., 2011a)	0.49 (Hammond et al., 2011c)	N/A[d]	N/A[d]	72.00 (Hammond et al., 2011c)	3.90 (Hammond et al., 2011c)	0.0003 (IoP, 2000)	0.0037 (IoP, 2000)
New Wood Product	NR[f]	NR[f]	NR[f]	NR[f]	10.00 (Hammond et al., 2011a)	0.71 (Hammond et al., 2011a)	N/A[d]	N/A[d]
Rubber (synthetic)	NR[f]	NR[f]	NR[f]	NR[f]	91.00 (Hammond et al., 2011c)	2.66 (Hammond et al., 2011c)	N/A[d]	N/A[d]
Ethylene, propylene, benzene and butadiene	NR[f]	NR[f]	NR[f]	NR[f]	N/A[d]	N/A[d]	N/A[d]	N/A[d]
PVCs	3.6[e]	1.284[e]	N/A[d]	N/A[d]	77.00 (Hammond et al., 2011c)	2.61 (Hammond et al., 2011c)	N/A[d]	N/A[d]
Batteries[a]	78.90[b] (Shell UK, 2017b)	22.37[b,c] (Li et al., 2023)	N/A[d]	N/A[d]	N/A[d]	N/A[d]	N/A[d]	N/A[d]

[a] In the absence of data on battery types, a lithium-ion battery was assumed.
[b] Average value assumed.
[c] $CO_{2\text{-eq}}$ was considered.
[d] Not applicable or no available data. Given their negligible contribution to the material inventories of the case studies, excluding them is not expected to significantly affect the energy and emissions estimates.
[e] Based on the sources from industry.
[f] Assumed as not recyclable.

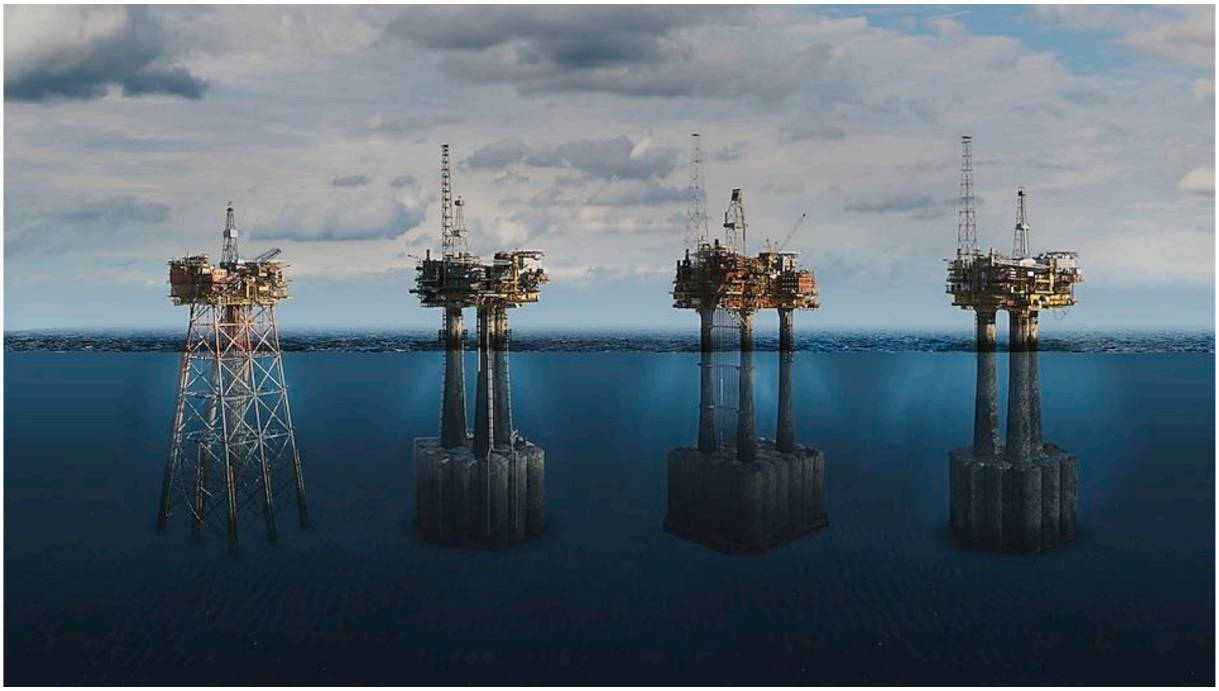


Fig. 4. Offshore O&G platforms in the Brent field (Shell UK, 2017).

this section are independent of project type and are intended to apply across multiple projects. By contrast, the duration parameters discussed in subsections 3.2 and 3.3 are project-specific and are set for each project based on available data from relevant sources. The following subsections present the selected values for the fuel consumption, emission, and energy demand parameters. The values of WoW and durational parameters

Table 7
Material inventory for the different platform topsides in the Brent field.

Material	Topsides Weights (tonne)				Recyclability (β_i)
	Alpha (Shell UK, 2017b)	Bravo (Shell UK, 2017b)	Charlie (Shell UK, 2017b)	Delta (Shell UK, 2015)	
ABS	2	2	2	2	
Alloyed Steel (including stainless steel)	**675**	**1634**	**2061**	**1926**	**98% (Shell UK, 2017; Oil and Gas Journal, 2024)**
Aluminium	**419**	**15**	**15**	**65**	**95% (Kouloumpis and Azapagic, 2022)**
Aluminium bronze	1	1	1	N/A	
Anodes (total)	419	N/A	N/A	N/A	
Asbestos (total)	4	9	9	10	
Batteries	**28**	**16**	**36**	**31**	**50% (Eurostat, 2025)**
Brass	1	1	1	N/A	N/A
Bronze	1	1	1	N/A	N/A
Buna	1	1	1	N/A	N/A
Butyl rubber	2	2	2	2	N/A
Carbon steel	**11,921**	**19,572**	**25,448**	**19,781**	**98% (Shell UK Limited, 2017a; Oil and Gas Journal, 2024)**
Cement (powder)	2	N/A	N/A	N/A	N/A
Ceramics	5	5	5	5	N/A
Chartex/fire protection	27	103	122	80	N/A
Copper	**107**	**222**	**281**	**84**	**95% (Kouloumpis and Azapagic, 2022)**
Copper nickel alloys	67	174	229	309	N/A
Cork	2	2	2	2	N/A
Cotton	2	5	5	6	N/A
Drill cutting residues	12	12	12	12	N/A
EPDM- cables	23	5	23	11	N/A
Ethylene, propylene, benzene and butadiene	**97**	**53**	**145**	**98**	0%*
Formica	2	2	2	2	N/A
Glass	5	5	5	5	N/A
GRP	7	21	16	20	N/A
Graphite/charcoal	0.1	0.1	0.1	N/A	N/A
Gun metal	1	1	1	N/A	N/A
Inconel/nimonics	6	13	13	13	N/A
Insulation	31	99	83	104	N/A
Iron (cast)	3	3	3	3	N/A
Lead	11	6	13	11	N/A
LSA scale (NORM)	22	43	323	69	N/A
Melamine	1	1	1	N/A	N/A
Monel	0.1	0.1	0.1	N/A	N/A
Neoprene	5	5	5	5	N/A
Ni-resist	10	10	10	10	N/A
Nylon	10	10	10	10	N/A
Paint	930	961	899	899	N/A
PTFE- seals	0.1	0.1	0.1	N/A	N/A
Plastics	4	3	4	5	N/A
PVC	**32**	**19**	**65**	**61**	**35% (PVC Recycling, 2026)**
Residual HC	7	<1	<1	N/A	N/A
Rubber	**20**	**20**	**20**	**20**	**0%***
Sewage	1	1	1	N/A	N/A
Tin	1	1	1	N/A	N/A
Titanium	28	31	32	31	N/A
Wood	**20**	**20**	**20**	**7**	N/A
Zinc	**537**	**532**	**519**	**499**	N/A
Total	15,068	23,636	30,423	24,186	

Note: Due to the limited availability of emission and energy-use factors across material types, only the major materials shown in bold and underlined are considered in this study.
* Assumed in this study.

are discussed for each case study in Section 5.

4.1. Fuel consumption parameters

Vessels involved in the decommissioning of platform topside and jacket structures consume significant amounts of fuel that should be accounted for in environmental analyses. The fuel consumption varies by vessel type and across operational modes. Table 3 lists the fuel types and fuel consumption rates for each vessel type. Among them, the SLV is the most fuel-intensive. The emission and energy demand factors for various fuel types are also presented in Table 4.

4.2. Onshore material flow parameters

Onshore operations are also subject to significant uncertainties due to variations in onshore dismantling equipment, locations of recycling facilities, and transport modes. Table 5 lists the selected values and provides the rationale for selecting the energy demand, emission, fuel consumption, and distance parameters associated with onshore dismantling, processing, and transport operations. As shown in Table 5, some of the parameters are sourced from IoP guidance (2000), while others are based on published references or available experience in the decommissioning sector.

Table 8
The duration parameters for the different vessel types involved in the Brent platforms topsides removal operations.

Operations	Vessel	Mobilisation		Transit		In field/operation		WoW	
		Notation	Value	Notation	Value	Notation	Value	Notation	Value
O_0	SLV	$t_{m,T}^{SLV}$	2[a]	$t_{tr,T}^{SLV}$	2.0[b]	$t_{o,T}^{SLV}$	2[c]	α_0	0.20[g] (ConocoPhillips, 2018)
O_1	BV	$t_{m,T}^{BV}$	1 [a]	$t_{tr,T}^{BV}$	1.20[d]	$t_{o,T}^{BV}$	2[e]	α_1	0.20[g] (ConocoPhillips, 2018)
O_2	TB	$t_{m,T}^{TB}$	1 [a]	$t_{tr,T}^{TB}$	1.20[d]	$t_{o,T}^{TB}$	2[a]	α_2	0.20[g] (ConocoPhillips, 2018)
O_3	AHV (OSV)	$t_{m,T}^{AHV}$	1 [a]	$t_{tr,T}^{AHV}$	1.20[d]	$t_{o,T}^{AHV}$	2[a]	α_3	0.20[g] (ConocoPhillips, 2018)
O_4	SBV	$t_{m,T}^{SBV}$	1 [a]	$t_{tr,T}^{SBV}$	2.40[b]	$t_{o,T}^{SBV}$	2[f]	α_4	0.20[g] (ConocoPhillips, 2018)

[a] Assumed in this study.
[b] Brent decommissioning progress report (Shell UK , 2020) stated a transit time of about 57 h (i.e., 2.40 days). Accordingly, 2 days for SLV and 2.40 days for the SBV are assumed.
[c] Brent topsides DP (Shell UK , 2018) reported 2 days for single lift operation in the field.
[d] Brent decommissioning progress report (Shell UK , 2020) considered about 29 h of transit time for the BV and TB.
[e] Brent decommissioning progress report (Shell UK , 2020) assumed 2 days for offloading time of topside from the BV at the recycling facility.
[f] It is assumed the SBV will be present at the field during the single lift operation by the SLV.
[g] A 20% of weather delay for sea surface operation was assumed, based on the Viking comparative assessment (CA) (ConocoPhillips, 2018).

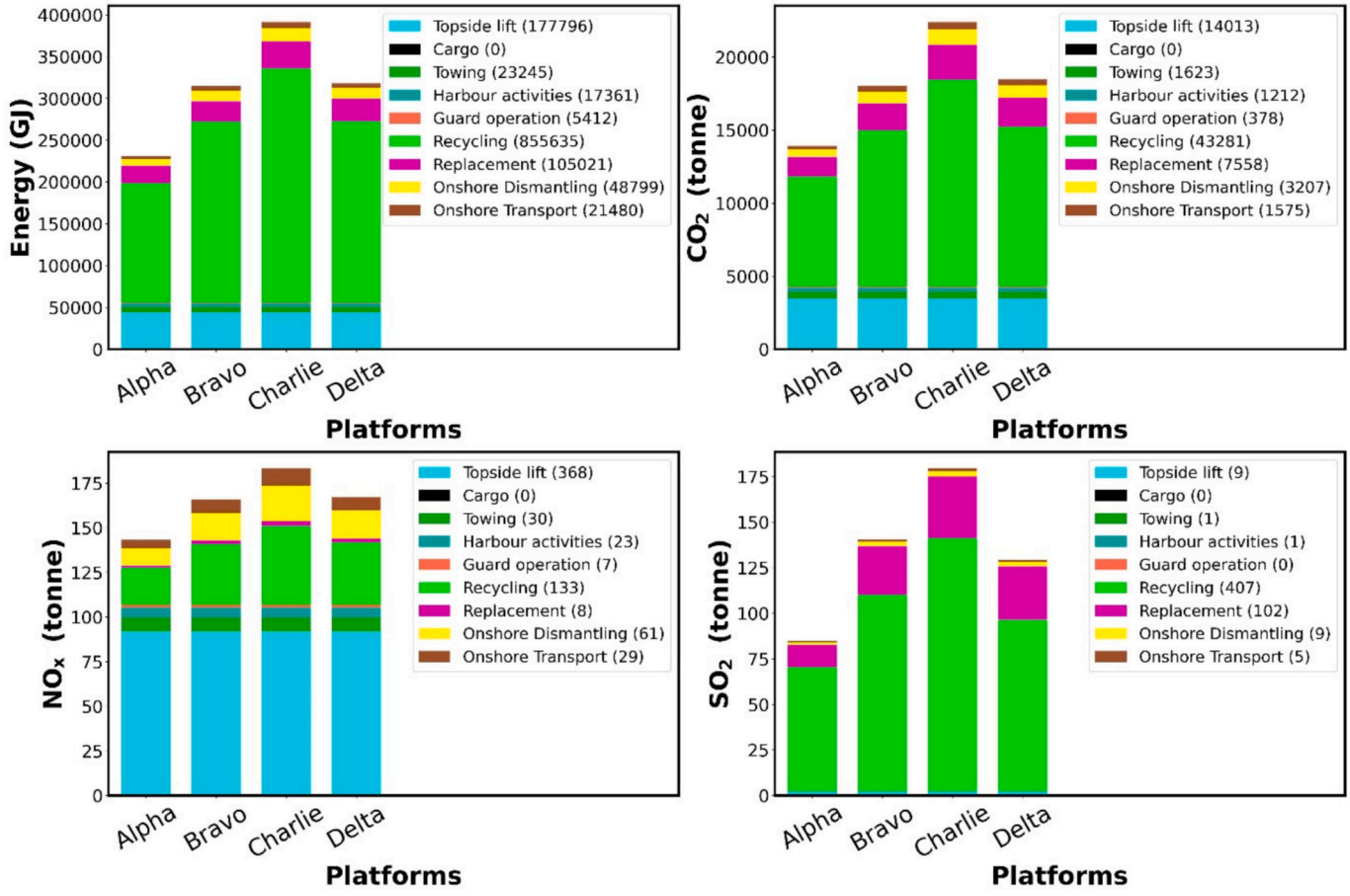


Fig. 5. Comparison of the energy demand and GHG emissions from decommissioning the Brent platform topside structures.

4.3. Material recycling and replacement parameters

The energy demand and emissions associated with material recycling and replacement are presented in Table 6. Some materials recovered from removal operations, such as steel and aluminium, are recyclable, whereas recycling of other materials is not currently feasible. Accordingly, in the formulations, energy demand and emission factors for recycling are applied to recyclable materials, and replacement factors are used for the non-recyclable materials.

The IoP guidance (2000) provides energy demand and emission factors for the recycling and manufacturing of various materials. However, given the age of the IoP guidance (2000), these factors may be outdated due to technological advances in material manufacturing and recycling. To incorporate up-to-date data, this study uses energy demand and CO_2 emission factors from the Inventory of Carbon and Energy (ICE) (Hammond et al., 2011b) as well as other references. For NO_X and SO_2, the values are primarily adopted from the IoP (2000). In addition, sufficient data were not available for some materials (e.g., rubber, ethylene, PVC). Because the amounts of these materials on platform topsides are negligible compared with other materials, particularly steel, omitting their recycling and replacement emissions and energy demand is not expected to have a significant impact on the

Table 9
Numerical comparison of the energy demand and emissions obtained from the proposed bottom-up EEA approach to those reported in the Brent DPs environmental statement (DNV, 2017) for decommissioning the Brent platforms' topsides.

Operations	Energy (GJ)		Emissions (tonne)					
			CO_2		NO_x		SO_2	
	This Study	Brent DPs (DNV, 2017)	This Study	Brent DPs (DNV, 2017)	This study	Brent DPs (DNV, 2017)	This study	Brent DPs (DNV, 2017)
Marine operations	223,813	254,958	17,227	19,423	428	527	11	284
Material Recycling	855,635	837,199	43,281	38,852	133	135	407	407
Material not recycled	105,021	42,125	7558	N/A[a]	8	N/A[a]	102	N/A[a]
Onshore Dismantling	48,799	43,511	3207	3200	61	71	9	3
Onshore Transport	21,480	21,340	1575	1570	29	35	5	1
Total	1,254,748	1,199,133	72,847	63,045	660	768	534	695
Difference	+4.6%		+15.5%		−14.0%		−23.1%	

[a] Not available in Brent DPs environmental statement (DNV, 2017).

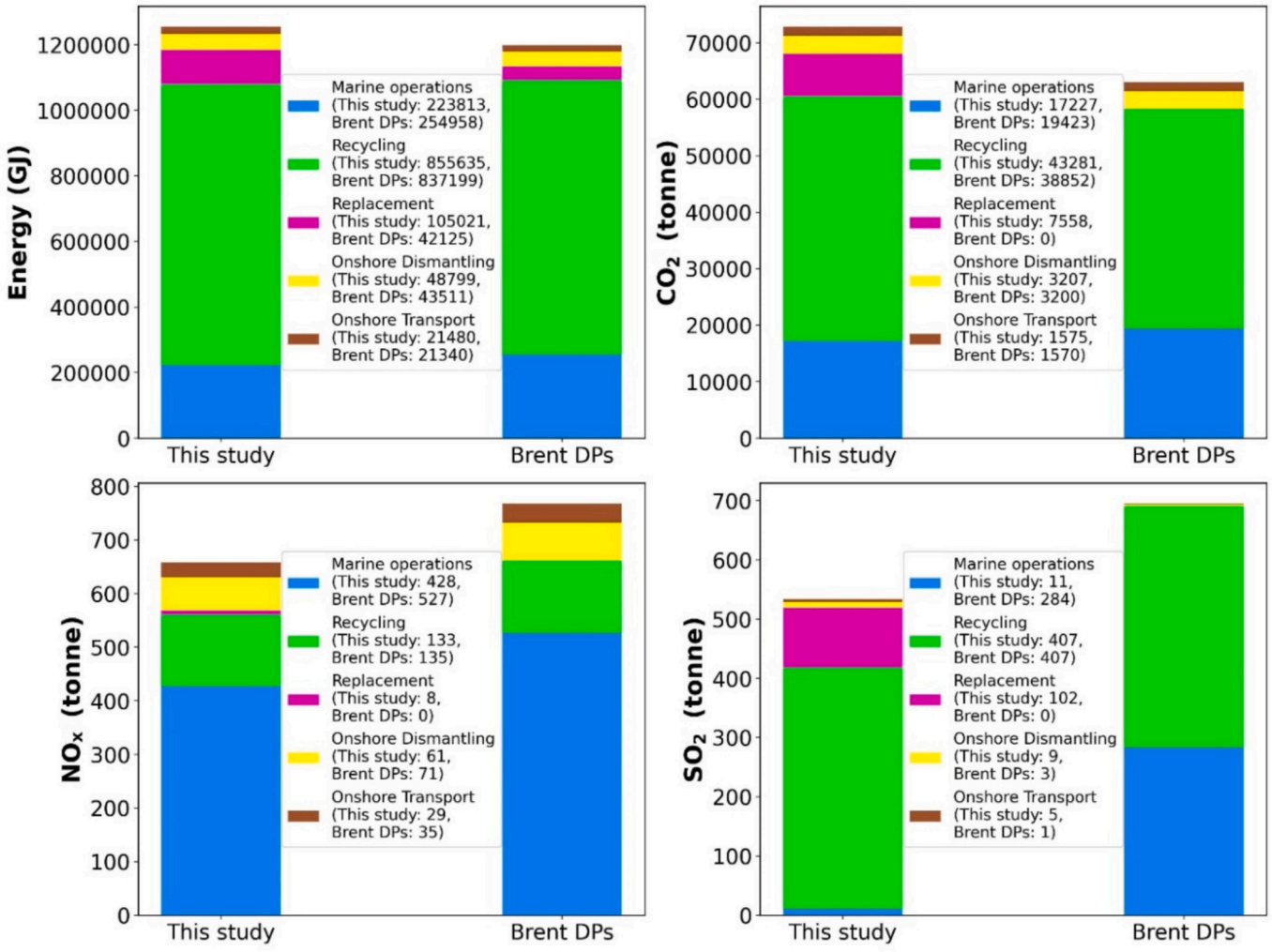


Fig. 6. Comparison of the overall energy demand and emissions obtained using the proposed bottom-up EEA approach with those reported in the Brent DPs environmental statement (DNV, 2017) for the decommissioning of the Brent platforms' topsides.

final estimates.

5. Numerical results

To validate the proposed EEA approach, two case studies are examined: the Brent topsides and jacket and the Tern jacket.

5.1. Brent case study

The Brent O&G field, located in the East Shetland Basin in Block 211/29 between the Shetland Islands and Norway, was commissioned in the 1970s (Shell UK, 2026). The field consisted of four platforms, including Brent Alpha, Brent Bravo, Brent Charlie, and Brent Delta, as well as pipelines and subsea structures (Fig. 4). The Brent Alpha platform was

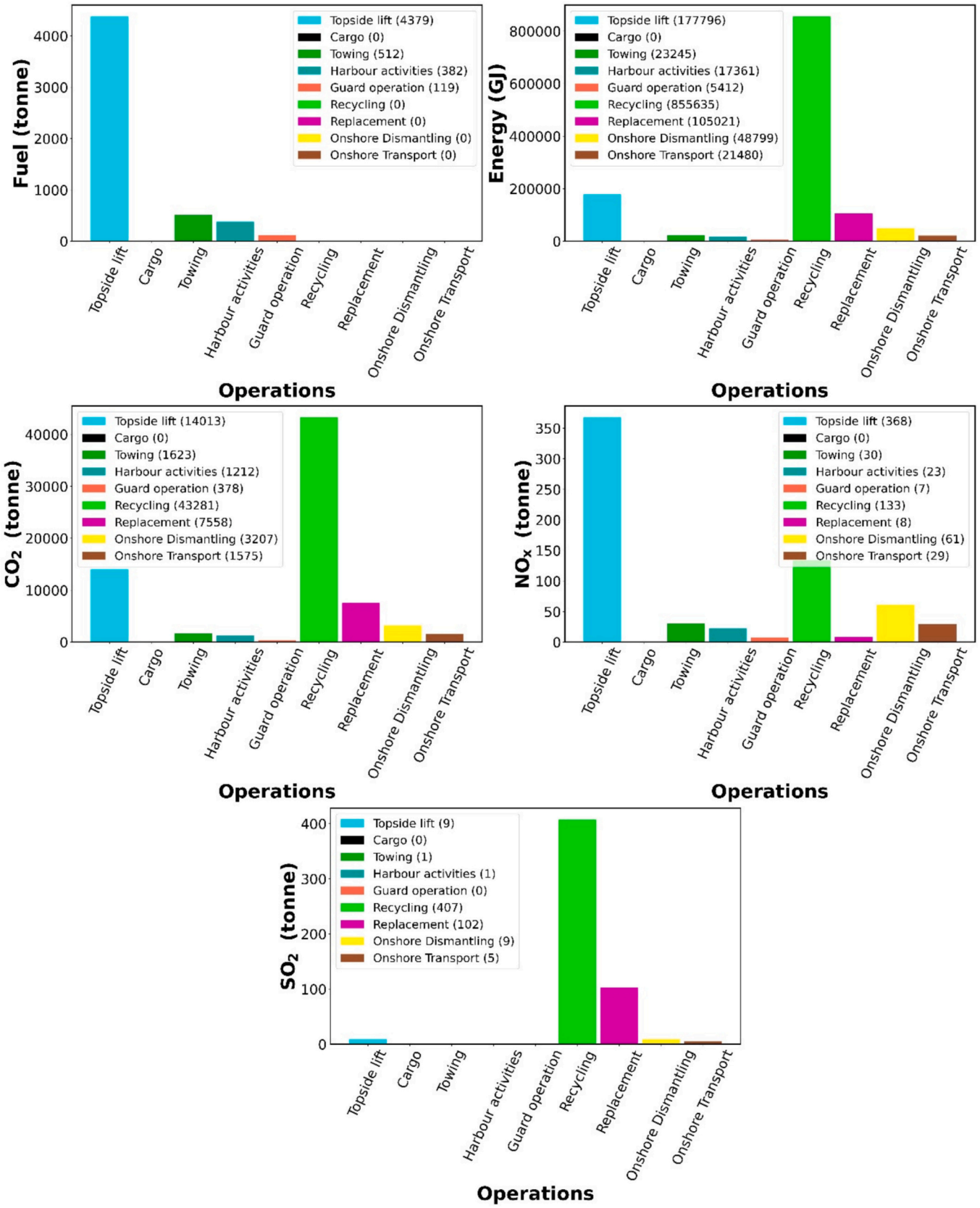


Fig. 7. Comparison of fuel consumption, energy demand, and emissions for various offshore and onshore operations, calculated using the proposed bottom-up EEA approach for the decommissioning of the Brent platforms' topsides.

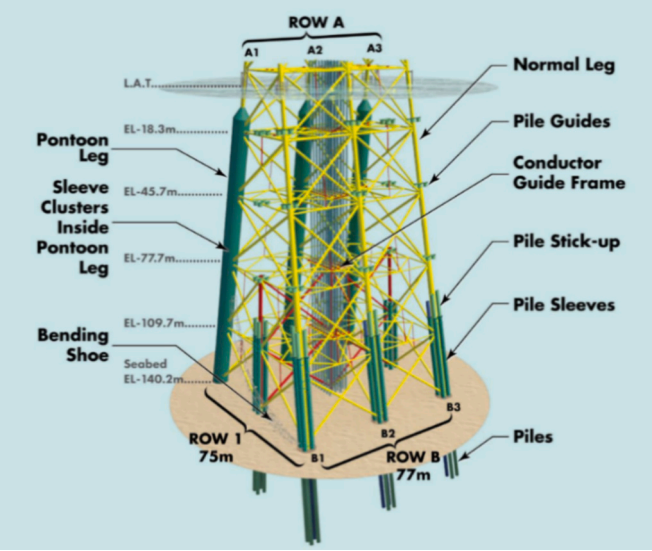


Fig. 8. Brent Alpha jacket structure (Shell UK, 2017).

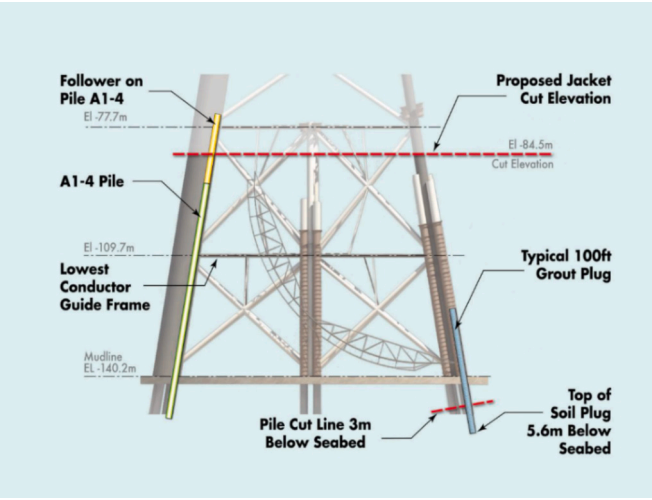


Fig. 9. Cut line for the upper jacket section (Shell UK, 2017).

Table 10
Material inventory for the upper Brent Alpha jacket structure above the cutline (Shell UK, 2017; Shell UK, 2017b; DNV, 2017).

Material	Weight (tonne)	Recyclability (β_i)
Standard Steel	8411	98% (Shell UK, 2017a; Oil and Gas Journal, 2024)
Aluminium/Zinc anodes	101	95% (Kouloumpis and Azapagic, 2022)
Marine growth	1601	N/A
Total	10,113	

supported by a steel jacket structure weighing 31,500 t, whereas the support structures for the other platforms are gravity-based structures weighing more than 300,000 t each (Shell UK, 2017a). After five decades of O&G production, the Brent field produced all economically recoverable reserves and entered the decommissioning phase. In the following subsections, the results obtained by the proposed EEA approach are separately discussed for the Brent topsides and Brent Alpha jacket decommissioning projects.

5.1.1. Brent platform topsides decommissioning

The material inventories for the four Brent platform topsides are listed in Table 7. The material weights are taken from the Brent topsides decommissioning technical document (TD) (Shell UK, 2017b) and the Brent Delta DP (Shell UK, 2015). Due to the limited availability of emission and energy-use factors across material types, only the major materials are included in this study; these are shown in Table 7 in bold and underlined. The considered material inventories cover 92%, 93%, 94%, and 93% of materials in the Brent Alpha, Bravo, Charlie, and Delta platforms, respectively.

Table 8 lists vessel duration and WoW parameters associated with the topside removal operations, along with the sources supporting these assumptions. These parameters include the durations needed for vessels and equipment to perform offshore operations. Mobilisation duration represents the time required to prepare and deploy vessels and equipment to the site for a specific offshore operation. The duration depends on vessel types, operation type, contract conditions, and service provider. According to the Brent decommissioning close-out report (Shell UK, 2019), the Pioneering Spirit vessel mobilised from Rotterdam on 25 April 2017 and entered the platform safety zone on 28 April 2017, suggesting approximately two days of mobilisation and two days of transit. Accordingly, a mobilisation duration of two days is assumed in this study for the SLV. A mobilisation duration of one day is assumed for the remaining vessels, following Jalili et al. (2025).

Fig. 5 compares energy demand and greenhouse gas (GHG) emissions for the Brent Alpha, Bravo, Charlie, and Delta platforms. Brent Charlie has the highest energy demand and emissions among the four platforms. In terms of emissions, decommissioning the Brent Charlie emits about 22,407 t of CO_2; the corresponding values for Brent Alpha, Bravo, and Delta are about 13,923 t, 18,047 t, and 18,468 t of CO_2, respectively. Removing the Brent Charlie platform results in the use of about 391,420 GJ of energy, compared with 230,810 GJ, 314,612 GJ, and 317,907 GJ for Alpha, Bravo, and Delta, respectively. By operation type, lifting, material recycling, and material replacement are the major contributors to energy demand and GHG emissions, mainly due to the use of the single-lift vessel (SLV), which is highly fuel-intensive.

As the Brent DPs environmental statement (DNV, 2017) has reported the overall energy demand and GHG-emission results for all platforms, the numerical comparisons in this section are based on these overall results. The detailed operational durations, energy demand, and emissions calculated by the proposed approach for the topsides removal operations are provided in Table B.1 in Appendix B, in which the offshore and onshore decommissioning operations result in approximately 1.25 million GJ of energy use and 73,000 t of CO_2 emissions. Table 9 summarises comparisons of energy demand and emission values from the proposed bottom-up approach with those reported in the Brent DPs environmental statement (DNV, 2017).

Table 9 shows that the proposed approach yields energy demand estimate within 5% of Ref. (DNV, 2017). However, differences are larger for CO_2, NO_x, and SO_2; the proposed approach estimates higher CO_2 and lower NO_x and SO_2, likely due to different emission factors used here versus those in (DNV, 2017). Given the extent of the assumptions and uncertainties in this study, these differences are considered acceptable from an engineering-estimation standpoint.

Fig. 6 graphically compares energy demand and emissions obtained from this study with those reported in the Brent DPs environmental statement (DNV, 2017). As shown in Fig. 6, the results from this study are in a good agreement with those in (DNV, 2017). The fuel consumptions, energy demand, and emissions associated with each operation in topside removal campaign are also compared in Fig. 7, where topside lifting and material recycling operations are the main contributors.

5.1.2. Brent alpha jacket decommissioning

The Brent Alpha platform was supported by a 161.9 m tall steel jacket structure weighing 31,453 t (Shell UK, 2017), including the

Table 11
The durational parameters for the different vessel types involved in the decommissioning of the Brent Alpha upper jacket structure.

Vessel(s)	Mobilisation/de-mobilisation		Transit		In field/operation		WoW	
	Notation	Value	Notation	Value	Notation	Value	Notation	Value
HLV	$t_{m,J}^{HLV}$	1[a]	$t_{tr,J}^{HLV}$	1[a]	$t_{o,J}^{HLV}$	16.33[c]	α_0	0.70[e] (ConocoPhillips, 2018)
ROVSV	$t_{m,J}^{ROVSV}$	1[a]	$t_{tr,J}^{ROVSV}$	1[a]	$t_{o,J}^{ROVSV}$	23.33	α_1	0.70[e] (ConocoPhillips, 2018)
SLV	$t_{m,J}^{SLV}$	2[a]	$t_{tr,J}^{SLV}$	2.10[b]	$t_{o,J}^{SLV}$	1[f]	α_2	0.70[e,g] (ConocoPhillips, 2018)
BV and TB	$t_{m,J}^{TB}$	1[a]	$t_{tr,J}^{TB}$	1[a]	$t_{o,J}^{TB}$	1.33[h]	α_3	0.20[d] (ConocoPhillips, 2018)

[a] Assumed in this study.
[b] Based on the Brent Alpha topside DP (Shell UK , 2020), the transit duration from the Brent field to the nearshore load transfer side near River Tees is about 38 h. According to the Brent jacket TD (Shell UK, 2017), transferring the jacket to the BV takes about 12 h. Hence, the SLV transit plus load-transfer time is estimated at approximately 2.10 days.
[c] Based on the Brent jacket TD (Shell UK, 2017), there are 28 conductors. Using an ROVSV, deployment of the DWC takes about 0.5 h, attachment and cutting take 5 h, retrieval takes 0.5 h, and replacing the wire takes 1 h. Therefore, the time per cut is approximately 7 h, yielding a total cutting duration of $7 \times 28 = 196$ hours. Assuming 12-h shifts, this corresponds to about $196/12 \approx 16.33$days to cut all conductors.
[d] A 20% of weather delay for sea surface operation was assumed, based on the Viking CA (ConocoPhillips, 2018).
[e] A 70% of weather delay for subsea operations was assumed, based on the Viking CA (ConocoPhillips, 2018).
[f] Based on Brent jacket TD (Shell UK, 2017), lifting the upper-jacket section with the SLV takes about 18 h. Allowing for SLV waiting time for final cuts, the lift duration is assumed to be 1 day.
[g] A 70% of WoW assumed, as it includes the subsea cutting operations.
[h] Brent jacket TD (Shell UK, 2017) reports 12 h for transferring jacket from SLV to the BV, 8 h towing BV from load transfer location to the port, and 12 h for skidding the jacket across from the BV to the quay. Therefore, the total operational time is approximately 1.33 days.

Table 12
Numerical comparison of the energy demand and emissions obtained from the proposed bottom-up EEA approach to those reported by the Brent DPs (Shell UK, 2017b) for the Brent Alpha jacket decommissioning.

Operations	Energy (GJ)		Emissions (tonne)					
			CO_2		NO_x		SO_2	
	This Study	Brent DPs (Shell UK, 2017b)	This Study	Brent DPs (Shell UK, 2017b)	This Study	Brent DPs (Shell UK, 2017b)	This Study	Brent DPs (Shell UK, 2017b)
Marine operations	101,925	123,400	7422	9300	173	250	5	100
Material Recycling	81,992	82,800	3872	3800	14	10	34	30
Material Replacement	7056	N/A*	514	N/A*	1	N/A*	1	N/A*
Onshore Dismantling	5663	5100	372	400	7	8	1	0
Onshore Transport	2493	2400	183	200	3	4	0	0
Total	199,129	213,700	12,362	13,700	198	272	40	130
Difference	−6.8%		−9.7%		−27.2%		−69%	

* Not available/reported.

footings as shown in Fig. 8. The jacket comprised three large pontoon legs and three additional legs; the pontoon legs were approximately 7.32 m in diameter, and the other legs were 1.83–2.74 m in diameter. The jacket was piled into the seabed with 32 steel piles, each 1.83 m in diameter. There were 28 conductors with diameters ranging from 0.66 m to 0.76 m. According to the Brent DPs (Shell UK, 2017b), the upper section of the Brent Alpha jacket was cut and lifted, while the footings were left in place under derogation. It was proposed that the jacket be cut at approximately 84.5 m Lowest Astronomical Tide (LAT) (about 55.7 m above the seabed) (Shell UK, 2017), as shown in Fig. 9. Table 10 lists the material inventory of the Brent Alpha upper jacket section above the cutline (Shell UK, 2017).

In Table 11, the duration parameters for Brent Alpha jacket removal operations, together with the underlying assumptions and sources, are presented. Cutting the jacket elements and conductors is the most time-consuming activity in the campaign, taking approximately 23.33 days. Brent DPs (Shell UK Limited, 2017a) indicates that 40 cuts are required to separate the jacket from the footings. Using an ROVSV, it takes about 0.5 h to deploy the DWC, 5 h to attach and cut, 0.5 h to retrieve the DWC, and 1 h to replace the wire with a new one. Therefore, the time per cut is approximately 7 h, yielding a total cutting duration of $7 \times 40 = 280$ hours. Assuming work shifts of 12 hours per day, this corresponds to roughly $280/12 \approx 23.33$ days to complete all cuts and separate the jacket from the footings. The detailed calculation results obtained from the proposed approach for the durations, fuel consumption, energy demand, and emissions of each operation are presented in Table B. 2 in Appendix B, where the offshore and onshore jacket removal operations resulted in about 200,000 GJ of energy and 12,400 t of CO_2 emissions.

To verify the effectiveness of the proposed approach, the energy demand and emissions obtained in this study are compared with those reported in (Shell UK, 2017b). As shown in Table 12, the differences in energy demand and CO_2 values are small (less than 10%). However, differences are larger for NO_x and SO_2 emissions, likely due to different emission factors applied to offshore operations and material recycling/replacement in this study versus (Shell UK, 2017b). Fig. 10 graphically compares the overall energy demand and emissions from this study with those reported in the Brent DPs (Shell UK, 2017b) and shows good agreement in energy demand and CO_2 emissions, with relatively close agreement in NO_x emissions. The fuel consumptions, energy demand, and emissions related to each offshore and onshore operations are displayed in Fig. 11, indicating that cutting and recycling are the major contributors.

5.2. Tern case study

In this subsection, an additional case study is selected from another O&G field to show the applicability of the proposed approach to a wider range of decommissioning case studies. The Tern installation is a drilling

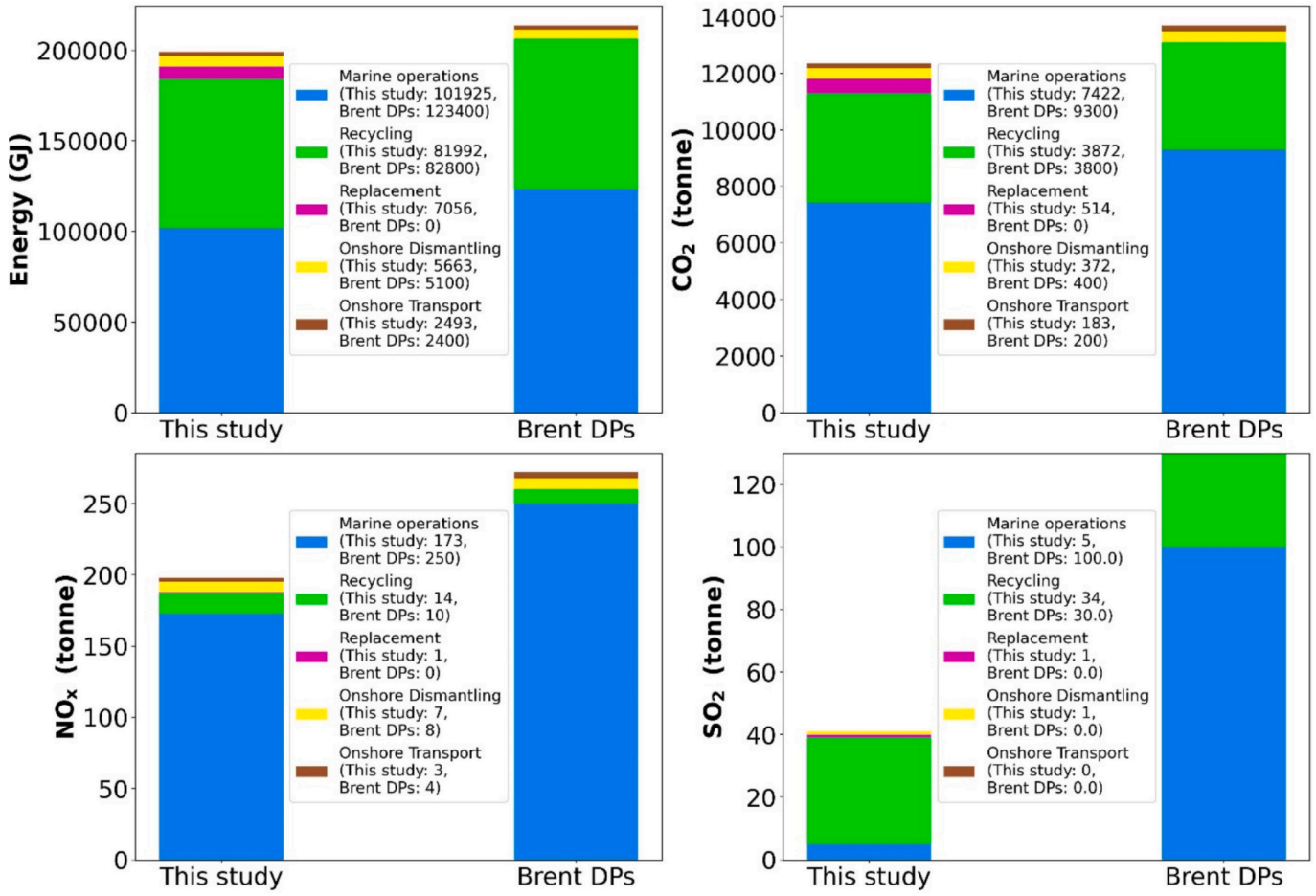


Fig. 10. Comparison of overall energy demand and emissions obtained using the proposed bottom-up EEA approach with those reported in the Brent DPs (Shell UK, 2017b) for the decommissioning of the Brent Alpha jacket.

and production unit located in Block 210/25 of the Northern North Sea, approximately 104 km northeast of Shetland and 47 km west of the UK-Norway median line (TAQA, 2024). The Tern jacket is an eight-legged steel structure with material inventory presented in Table 13.

The project details and complete set of assumptions are not available in the Tern DP (TAQA, 2024). However, for comparative purposes and to demonstrate the capabilities of the proposed EEA approach, the energy demand and emissions for Tern jacket are estimated in this study using a combination of parameters from the Brent case studies and Tern DP (TAQA, 2024). The Tern DP (TAQA, 2024) identifies vessels similar to those used in Brent case study. The duration data collected from the Tern DP (TAQA, 2024), summarised in Table 14, are used within the proposed model.

The energy demand and CO_2 emissions obtained from the proposed approach are compared with those reported by Tern DP (TAQA, 2024) in Table 15. The total energy demand estimated by the proposed approach is very close to that reported by Tern (TAQA, 2024), with a difference of nearly 5%. The main differences in energy demand arise in the onshore activities, likely due to assumptions not specified in the Tern DP (TAQA, 2024). The CO_2 emissions for the marine operations obtained by the proposed approach are very close to that reported in the Tern DP (TAQA, 2024); however, the CO_2 emissions for the material recycling and onshore activities do not align with those reported in (TAQA, 2024). The discrepancy in recycling emissions is likely related to the steel emissions factor used in this study, which are more recent than those suggested by IoP (2000) and typically used by O&G DPs. While this case study highlights the critical role of input data and assumptions in the quality of the energy demand and emissions estimates, it also supports the applicability of the proposed EEA approach to a wider range of O&G decommissioning case studies.

5.3. *Sensitivity of parameters*

Although the bottom-up nature of the proposed EEA approach is a strength in obtaining holistic emissions and energy demand results, its dependence on various durational parameters and on fuel consumptions, emission, and energy demand factors increases uncertainties in the results. This necessitates a rigorous uncertainty analysis of the input parameters. In the absence of reliable statistical data on these parameters, a sensitivity analysis is performed to show how CO_2 emissions change in response to variations across key parameter categories.

Fig. 12 illustrates the sensitivity of total CO_2 emissions for Brent topsides decommissioning (see sub-section 5.1) to changes in durational parameters, fuel consumption factors, and emission factors. Fig. 12 shows that the largest changes in CO_2 occur when the material recycling emission factors vary: a 25% change in recycling emission factors results

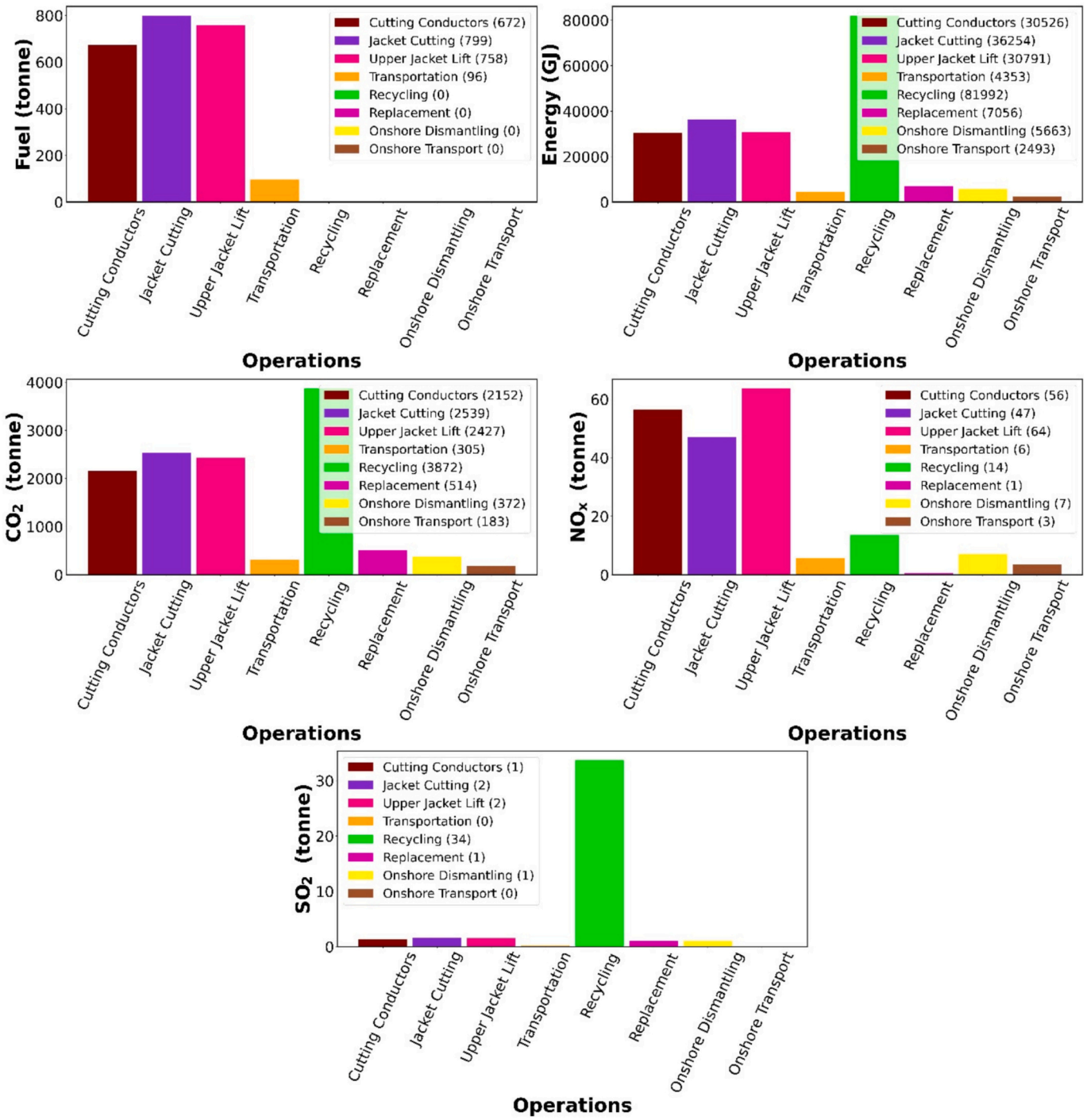


Fig. 11. Comparison of fuel consumption, energy demand, and emissions across offshore and onshore operations, estimated using the proposed bottom-up EEA approach for the decommissioning of the Brent Alpha jacket.

Table 13
Material inventory for the Tern jacket structure (TAQA, 2024).

Material	Weight (tonne)	Recyclability
Steel	12,845	Yes
Hazardous material/NORM	15	No
Other non-hazardous material (includes marine growth)	1940	No
Total	≈14,800	

in an approximately 15% changes in CO_2 emissions. By contrast, the impact of vessel mobilisation and operation durations on emissions is small relative to other parameters. Fuel consumption factors, transit duration, and material replacement emission factors have a moderate impact on emissions.

6. Concluding remarks

A bottom-up emissions and energy assessment (EEA) approach was proposed for decommissioning O&G platform topsides and jackets in the North Sea. The approach integrates multiple data types to estimate

Table 14
The durational parameters for the different vessel types involved in the decommissioning of the Tern jacket structure.

Vessel(s)	Mobilisation/de-mobilisation		Transit		In field/operation		WoW	
	Notation	Value	Notation	Value	Notation	Value	Notation	Value
HLV	$t_{m,J}^{HLV}$	1.5 (TAQA, 2024)	$t_{tr,J}^{HLV}$	7.33 (TAQA, 2024)	$t_{o,J}^{HLV}$	14.8 (TAQA, 2024)	α_0	0 (TAQA, 2024)
ROVSV	$t_{m,J}^{ROVSV}$	10 (TAQA, 2024)	$t_{tr,J}^{ROVSV}$	13 (TAQA, 2024)	$t_{o,J}^{ROVSV}$	16.2 (TAQA, 2024)	α_1	0 (TAQA, 2024)
SLV	$t_{m,J}^{SLV}$	2 (TAQA, 2024)	$t_{tr,J}^{SLV}$	2 (TAQA, 2024)	$t_{o,J}^{SLV}$	18.9 (TAQA, 2024)	α_2	0.05 (TAQA, 2024)
BV and TB[a]	$t_{m,J}^{TB}$	N/A	$t_{tr,J}^{TB}$	N/A	$t_{o,J}^{TB}$	0	α_3	N/A

[a] Not to be used in Tern DP (TAQA, 2024).

Table 15
Numerical comparison of energy demand and CO_2 emissions obtained from the proposed bottom-up EEA approach with those reported in the Tern DP (TAQA, 2024) for the decommissioning of the Tren jacket structure.

Operations	Energy (GJ)		CO_2 Emissions (tonne)	
	This Study	Tern DP (TAQA, 2024)	This Study	Tern DP (TAQA, 2024)
Marine operations	142,688	141,560	10,710	10,510
Material Recycling	120,743	126,765	5652	13,522
Material Replacement	22,736	N/A	1740	N/A
Onshore Dismantling	8379	16,198	551	N/A
Onshore Transport	3688	15	270	1
Total	298,233	284,537	18,923	24,033
Difference	+4.8%		−21.2%	

greenhouse gas (GHG) emissions and energy demand for offshore and onshore decommissioning operations, including field-specific information, duration parameters, vessels and equipment types, fuel consumption and emission factors, weather delays, onshore dismantling and transport, and material recycling and replacement. The lack of data is the main challenge to an effective EEA. To address this challenge, decommissioning programmes (DPs), environmental statements, technical reports, guidelines, and other references from the North Sea O&G decommissioning sector were reviewed, and appropriate values were adopted. Where required data were unavailable, the best-available engineering estimates were provided.

To verify the effectiveness of the proposed approach, the EEA of two real-world decommissioning case studies was investigated: the Brent platforms (topsides and jackets) and the Tern jacket. The numerical results show that decommissioning the four Brent platforms results in about 1.25 million GJ of energy demand and 73,000 t of CO_2 emissions. The Brent Charlie platform is the largest contributor, with 22,407 t of CO_2; the corresponding values for Brent Alpha, Bravo, and Delta are 13,923 t, 18,047 t, and 18,468 t of CO_2, respectively. Removal of the Brent Alpha steel jacket results in approximately 200,000 GJ of energy demand and 12,362 t of CO_2 emissions. The EEA for the Tern jacket decommissioning reveals approximately 300,000 GJ of energy demand and 19,000 t of CO_2 emissions.

The numerical comparisons revealed acceptable differences between the energy demand and GHG emission estimates from this study and those reported in the Brent and Tern DPs and their environmental statements. The differences in energy demand are within 7%: +4.6% for the Brent platform topsides, −6.8% for the Brent Alpha jacket, and + 4.8% for the Tern jacket. For CO_2 emissions, the differences are within 22%: +15.5%, −9.7%, and − 21.2% for the Brent platforms, Brent Alpha jacket, and Tern jacket, respectively. Given the extent of the assumptions and uncertainties in this study, these differences are considered

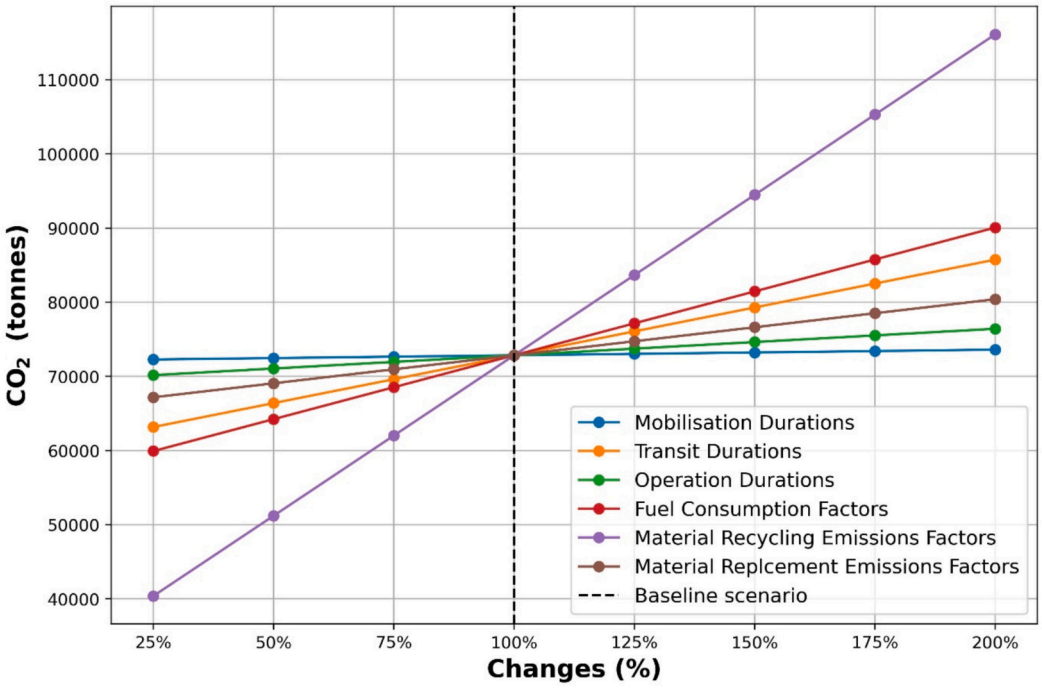


Fig. 12. Sensitivity of the total CO_2 emissions caused by the Brent topsides decommissioning activities to variations in duration parameters, fuel consumption factors, and emissions factors.

acceptable from an engineering-estimation standpoint. However, the differences in NO_x and SO_2 emissions obtained in this study are not consistent with the source values. These discrepancies are likely due to the use of different, often outdated, emission and energy demand factors in industry reports. This highlights the need for a unified, standardised inventory of emission and energy demand factors to enable reliable EEA for O&G decommissioning projects in the North Sea.

Due to its bottom-up nature, the proposed EEA approach relies on a set of parameters that are subject to uncertainty. A sensitivity analysis was performed to show how CO_2 emissions from the Brent topsides decommissioning vary in response to changes across key parameter categories. The results show that the largest changes in CO_2 emissions occur when material recycling emissions factors vary: a 25% change in recycling emissions factors results in an approximately 12.5% change in total CO_2 emissions. This underscores the need for reliable emission-factor data for material recycling to obtain more robust emissions estimates.

This study contributes to making the emissions and energy demand quantification more transparent for policy makers and broader stakeholders involved in O&G decommissioning projects. The bottom-up nature of the proposed approach enables high-quality emissions and energy demand estimates and allows future expansion and modification as new data and technologies become available. For example, integrating automatic identification system (AIS) vessel data with vessel specifications and mode-specific power demands into the approach could improve the accuracy of the results.

Weather delays are important considerations and should be accounted for using regional metocean data. In this study, EEA outcomes were derived using approximate assumptions for weather downtimes. Although sufficient for an initial assessment, results could be strengthened by incorporating statistical weather-delay analysis based on regional metocean data for the vessels involved in offshore operations.

This flexibility to update and refine inputs will help to provide more accurate figures for the GHG emissions and energy demand and support a better understanding of the environmental impacts of offshore O&G decommissioning projects. The proposed EEA approach will be useful in assisting stakeholders and informing decision-making in future O&G decommissioning projects.

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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.

Appendix A. List of parameters

Table A.1
General parameters.

Parameter	Unit	Definition
O_i	N/A	*i*th offshore operation
N	units	Number of topsides or jackets
n_i	number	Number of operations in the *i*th topside or jacket removal campaign
n_m	number	Number of materials in the topside/jacket
w_i	tonne	The weight of the *i*th material in the topside/jacket
D	km	Distance from onshore site to the recycling facility
β_i	number	Recycling percentage of the *i*th material

Table A.2
Duration parameters.

Parameter	Unit	Definition
$t_{m,T}^{SLV}$	day	Mobilisation duration of the SLV for topside removal
$t_{tr,T}^{SLV}$	day	Transit duration of SLV during the topside removal
α_j	number	WoW coefficient for the *j*th operation in the topside or jacket removal campaign
$t_{o,T}^{SLV}$	day	Operational duration of the SLV during the topside removal
$t_{m,T}^{TB}$	day	Mobilisation duration of the TB for topside removal
$t_{tr,T}^{TB}$	day	Transit duration of TB during the topside removal
$t_{o,T}^{TB}$	day	Operational duration of the TB during the topside removal
$t_{m,T}^{AHV}$	day	Mobilisation duration of the AHV for topside removal
$t_{tr,T}^{AHV}$	day	Transit duration of AHV during the topside removal
$t_{o,T}^{AHV}$	day	Operational duration of the AHV during the topside removal
$t_{m,T}^{SBV}$	day	Mobilisation duration of the SBV for topside removal
$t_{tr,T}^{SBV}$	day	Transit duration of SBV during the topside removal
$t_{o,T}^{SBV}$	day	Operational duration of the SBV during the topside removal
$t_{m,J}^{HLV}$	day	Mobilisation duration of the HLV for cutting operation of the conductors in the jacket removal campaign
$t_{tr,J}^{HLV}$	day	Transit duration of HLV during the cutting operation of the jacket conductors
$t_{o,J}^{HLV}$	day	Operational duration of the HLV during the jacket conductors cutting operation
$t_{m,J}^{ROVSV}$	day	Mobilisation duration of the ROVSV for jacket cutting operation
$t_{tr,J}^{ROVSV}$	day	Transit duration of ROVSV during the jacket cutting operation

(*continued on next page*)

Table A.2 (*continued*)

Parameter	Unit	Definition
$t_{o,J}^{ROVSV}$	day	Operational duration of the ROVSV during the jacket cutting operation
$t_{m,J}^{SLV}$	day	Mobilisation duration of the SLV for jacket lifting operation
$t_{tr,J}^{SLV}$	day	Transit duration of SLV during the jacket lifting operation
$t_{o,J}^{SLV}$	day	Operational duration of the SLV during the jacket lifting operation
$t_{m,J}^{TB}$	day	Mobilisation duration of the TB for jacket shipping operation to shore
$t_{tr,J}^{TB}$	day	Transit duration of the TB during the jacket shipping operation to shore
$t_{o,J}^{TB}$	day	Operational duration of the TB during the jacket shipping operation to shore
t_m	day	Mobilisation duration of a vessel
t_{tr}	day	Transit time of a vessel to and from the site
t_o	day	The operational time of a vessel
t_w	day	Delays in an operation due to weather conditions
t_i	day	The duration of the *i*th operation

Table A.3
Energy demand parameters.

Parameter	Unit	Definition
E	GJ	Overall energy demand during the removal and recycling operations
E^{off}	GJ	Energy demand related to the offshore removal operations
E^{on}	GJ	Energy demand related to the onshore removal operations
e_j	GJ/t	Energy content of the fuel consumed in the *j*th operation
E^{odp}	GJ	The energy demand by the onshore dismantling and processing
E^{otr}	GJ	The energy demand resulted from the onshore transport of removed topside/jacket materials to the recycling centre
E^{rp}	GJ	The energy demand during the recycling process of topside/jacket materials
e^{odp}	GJ/t removed material	Energy demand by the onshore dismantling and processing of topside/jacket components
e^{otr}	GJ/ t material /km	Energy demand resulted from the transport of materials from onshore dismantling centre to the recycling facility
e_i^r	GJ/t	Energy demand by the recycling of the *i*th material
e_i^p	GJ/t	Energy demand by the production of the *i*th material

Table A.4
Fuel consumption parameters.

Parameter	Unit	Definition
f_j	tonne	Fuel consumption of the *j*th operation
f_j^T	tonne	Fuel consumption of the *j*th topside removal operation
f_j^J	tonne	Fuel consumption of the *j*th jacket removal operation
f_m^{SLV}	tonne/day	Fuel consumption rate of SLV in mobilisation
f_{tr}^{SLV}	tonne/day	Fuel consumption rate of SLV in transit
f_o^{SLV}	tonne/day	Fuel consumption rate of SLV at operational mode
f_m^{TB}	tonne/day	Fuel consumption rate of TB in mobilisation
f_{tr}^{TB}	tonne/day	Fuel consumption rate of TB in transit
f_o^{TB}	tonne/day	Fuel consumption rate of TB at operational mode
f_m^{AHV}	tonne/day	Fuel consumption rate of AHV in mobilisation
f_{tr}^{AHV}	tonne/day	Fuel consumption rate of AHV in transit
f_o^{AHV}	tonne/day	Fuel consumption rate of AHV at operational mode
f_m^{SBV}	tonne/day	Fuel consumption rate of SBV in mobilisation
f_{tr}^{SBV}	tonne/day	Fuel consumption rate of SBV in transit
f_o^{SBV}	tonne/day	Fuel consumption rate of SBV at operational mode
f_m^{HLV}	tonne/day	Fuel consumption rate of HLV in mobilisation
f_{tr}^{HLV}	tonne/day	Fuel consumption rate of HLV in transit
f_o^{HLV}	tonne/day	Fuel consumption rate of HLV at operational mode
f_m^{ROVSV}	tonne/day	Fuel consumption rate of ROVSV in mobilisation
f_{tr}^{ROVSV}	tonne/day	Fuel consumption rate of the ROVSV in transit
f_o^{ROVSV}	tonne/day	Fuel consumption rate of ROVSV at operational mode
f^{otr}	tonne fuel/t material	Fuel consumed by onshore transport of removed materials to the recycling facility

Table A.5
Emissions parameters.

Parameter	Unit	Definition
ε	tonne of pollutant	Overall emissions caused by the topside/jacket removal and recycling operations
ε^{off}	tonne of pollutant	Emissions produced by the offshore operations during the topside/jacket removal
ε^{on}	tonne of pollutant	Emissions caused by the onshore operations during the topside/jacket removal
ε_j	tonne of pollutant/t of fuel	Emission factor of the fuel consumed in the *j*th operation
ε^{odp}	tonne of pollutant	Emissions resulted from the onshore dismantling and processing of topside/jacket materials
ε^{otr}	tonne of pollutant	Emissions cause by the onshore transport of the topside/jacket materials to the recycling facility
ε^{rp}	tonne of pollutant	Emissions produced by the recycling/replacement process of topside/jacket materials
ε^{odp}	tonne emitted/t material	Emissions caused by the onshore materials dismantling and processing
ε^{otr}	tonne emitted /tonne of fuel	Emission factors for the onshore transport
ε_i^r	tonne emitted /tonne	Emissions produced from recycling of the *i*th material
ε_i^p	tonne emitted /tonne	Emissions produced from manufacturing of the *i*th material

Appendix B. Detailed calculations

Table B.1
Calculated durations, fuel consumption, energy demand, and emissions obtained using the proposed bottom-up EEA approach for the decommissioning of the Brent platform topsides.

Operations	Vessel	Durations (days)	Fuel (tonne)	Energy (GJ)	Emissions (tonne)		
					CO_2	NO_x	SO_2
Topside lift	SLV	29.6	4379.2	177,796	14,013	368	8.76
Cargo[a]	BV	18.4	0	0	0	0	0
Towing	TB	18.4	512	23,245	1623	30	1.02
Harbour activities	AHV	18.4	382.4	17,361	1212	23	0.77
Guard operation	SBV	98.4	119.2	5412	378	7	0.24
Material Recycling	N/A	N/A	N/A	855,635	43,281	134	407.49
Material not recycled	N/A	N/A	N/A	105,021	7558	8	102.40
Onshore Dismantling	N/A	N/A	N/A	48,799	3207	61	8.71
Onshore Transport	N/A	N/A	N/A	21,480	1575	29	4.97
Total		183.2	5392.8	1,254,748	72,847	660	534.30

[a] BV is towed by TBs.

Table B.2
Calculated durations, fuel consumption, energy demand, and emissions obtained using the proposed bottom-up EEA approach for the decommissioning of Brent Alpha jacket.

Operations	Vessel	Durations (days)	Fuel (tonne)	Energy (GJ)	Emissions (tonne)		
					CO_2	NO_x	SO_2
Cutting Conductors	HLV	29.8	672	30,526	2152	56.5	1.35
Jacket Cutting	ROVSV	41.7	799	36,254	2539	47.12	1.60
Upper Jacket Lift	SLV	5.8	758	30,791	2427	63.71	1.52
Transportation	TB	3.6	96	4353	305	5.66	0.19
Material Recycling		N/A	N/A	81,992	3872	13.59	33.68
Material Replacement		N/A	N/A	7056	514	0.61	1.05
Onshore Dismantling		N/A	N/A	5663	372	7.08	1.01
Onshore Transport		N/A	N/A	2493	183	3.40	0.006
Total		80.818	2325	199,129	12,362	198	40.40

Data availability

Data will be made available on request.

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