Degree Program in Strategic Management

Course of Sustainable Strategies for Business Leaders

Integrating Circular Economy Practices in Oil & Gas Decommissioning: A Practical Framework

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ABBREVIATION

Abbreviation	Meaning
CE	Circular Economy
CoP	Cessation of Production
FPSO	Floating Production Storage and Offloading
IMO	International Maritime Organization
O&G	Oil and Gas industry
OSPAR	Oslo Convention for the Prevention of Marine Pollution
UKCS	UK Continental Shelf
UNCLOS	United Nations Convention on the Law of the Sea
WHPS	Wellhead Protection Structure

ABSTRACT

The offshore decommissioning activities within the oil and gas industry present a critical environmental challenge, necessitating a paradigm shift towards circular economy practices. The research aims to address the following research questions: How are the principles of the circular economy, specifically recycling, and reusing, manifested and integrated into oil and gas offshore decommissioning processes? How can the offshore decommissioning activities in the oil and gas industry effectively incorporate circular economy practices? A literature review regarding the oil and gas (O&G) offshore decommissioning activities and circular economy (CE) has been made (2). Accordingly, their intersection has been analysed identifying the main practices of the industry reusing the fields at their end-of-life (2.2). Therefore, five case studies of O&G offshore decommissioning in the UK Continental Shelf (UKCS) have been outlined (4), conducting a cross-case analysis determining patterns and trends, assessing success factors and identifying challenges faced (5). Consequently, a whole system and whole lifecycle framework were proposed for the integration of a CE into offshore O&G decommissioning (6), thereby also contributing to the CE literature by defining practical strategies. CE-related challenges and opportunities in these activities, which have been analysed in the literature review, can only be addressed effectively with a holistic approach, such as enabled by the framework, to avoid trade-offs and make the most of synergies.

Keywords: Circular Economy, Oil and Gas industry, Offshore Decommissioning, Reduce, Reuse, Recycle.

1. *Introduction*

1.1. Background and Rationale

The oil and gas industry (O&G) is vital to supporting economic growth and providing for global energy demands. With a significant portion of the world's carbon dioxide (CO2) emissions coming from both direct and indirect sources, the O&G industry assumes a critical role around environmental concerns. Its emissions account for a staggering 42% of all CO2 emissions worldwide (McKinsey & Company, 2023). Such a large carbon footprint highlights how urgent it is for the sector to address its environmental impact.

The O&G industry must decommission facilities that have reached the end of their useful lives among other difficult environmental and social issues. Over 12,000 O&G offshore platforms are currently present worldwide in the offshore energy industry (Ars & Rios, 2017). These offshore platforms are strategically positioned on the continental shelves of 53 countries (Parente et al., 2006), highlighting the offshore O&G industry's profound significance as a key player and global influencer. Many of these platforms' components were designed to last from 25 to 30 years. Therefore, a growing amount of offshore infrastructure is approaching or has already surpassed that lifespan (Nelson et al., 2021) and globally more than 2500 offshore O&G installations are anticipated to be decommissioned by 2040 (*Decommissioning*, 2020). According to S&P Global Commodity Insights (2021), the period from 2021 to 2030 is known as the "decade of offshore decommissioning," and it is predicted that global spending on offshore decommissioning will reach almost USD 100 billion during this period. Comparing this projection to the previous ten years, there has been a remarkable rise of over 200%. It is noteworthy that the European region accounts for the majority of this expenditure, making up roughly 33% of the overall expenditure (IHS Markit, 2021). Beyond the financial burden, decommissioning presents several challenges that stakeholders and regulators frequently run into, such as technical, environmental, and socio-economic (Fowler et al., 2014). An interconnection context is constituted by the environmental, social, technical, and economic considerations, as well as the related policy and governance framework that are involved in infrastructure decommissioning options (Elliott et al., 2020). Additionally, up until the middle of the century, more offshore O&G infrastructure installations were forecasted, especially for gas (Gourvenec et al., 2022). To reduce the negative effects on the nearby oceans and marine ecosystems, efficient and responsible decommissioning processes are required. A thorough decommissioning assessment takes into account a wider range of ecological, economic, and societal impacts in addition to the immediate environmental concerns. While keeping an eye on the interests and well-being of future generations, it attempts to strike a balance between minimising environmental risks, maximising resource use efficiency, and ensuring social equity (Ekins et al., 2006).

The idea of the circular economy (CE) has come to light as a potentially effective strategy for overcoming the weaknesses of the linear economic model, which is characterised by resource exhaustion and waste production.

The CE has been interpreted in more than a hundred different ways, according to the extensive body of literature. But out of all of these definitions, the one that best captures the fundamental ideas that are omnipresent among them is that it is an "economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes" (Kirchherr et al., 2017). As a result of increased stakeholder awareness and comprehension of sustainability issues, various industries are making greater efforts to harmonise the entire lifecycle of their products. This comprehensive approach takes into account each stage, from product sourcing and manufacturing to use and final disposal as well as the subsequent recovery of value from products at the end of their lifecycle (Jakhar et al., 2019). The CE promotes a change from the conventional linear economic model to a circular one, which not only promises increased value for businesses (Centobelli et al., 2020) but also offers a safe route to societal well-being and ecological equilibrium for future generations (Nikanorova et al., 2020).

This paradigm shift is consistent with more general sustainability objectives and presents an opportunity for the O&G industry to rethink decommissioning procedures. Decommissioning of O&G facilities and the adoption of CE practices present a unique opportunity to manage the environmental and social challenges involved in decommissioning as well as to contribute to a more sustainable future (Lindauere et al., 2020). Even though significant financial resources are currently being allocated, and there is a growing emphasis on cutting-edge approaches, there hasn't been much focus on developments involving the recycling or recovery and subsequent reuse of materials, components, subassemblies, or equipment during the decommissioning process. There aren't relevant case study analyses examining these aspects in the body of literature currently in existence. The main focus of research to date has been on shedding light on the opportunities and challenges related to the shifts of the O&G decommissioning sector towards more sustainable paradigms.

1.2. Research Objectives

Taking into consideration the aforementioned gap in the literature, this research's main objective is to examine how the oil and gas industry's decommissioning procedures integrate practices from the circular economy to suggest a practical framework for businesses looking to adopt CE principles within decommissioning projects. It does so by using a comparative case study methodology, thanks to which cases where CE practices have been successfully incorporated into decommissioning projects will be investigated and analysed. This process aims to identify trends, success factors, and obstacles related to the adoption of CE practices during decommissioning activities by conducting in-depth analyses of specific case studies. Therefore, a comparison matrix that links decommissioning methods with CE procedures will be developed. The degree of integration between CE principles and decommissioning activities will be evaluated across various case studies using this matrix as a visual representation. Hence, it will identify patterns, trends, and lessons learned about the successful adoption of CE practices in decommissioning by conducting a cross-case analysis of the identified case studies. This objective aims to identify common success factors, obstacles overcome, and strategies used by businesses to successfully integrate CE principles. Finally, the results of the cross-case analysis will be assembled into a comprehensive practical framework that outlines feasible suggestions for embracing CE principles within decommissioning activities.

1.3. Research Questions

The research questions that direct this study are the following, building on the context and research goals already established:

- *RQ₁: How are the principles of the circular economy, specifically recycling, and reusing, manifested and integrated into offshore oil and gas decommissioning processes?*
- *RQ₂: How can the decommissioning activities in the O&G industry effectively incorporate CE practices?*

These questions capture the ultimate objective of this research, which is to create a practical framework that helps businesses align their decommissioning efforts with CE principles. For answering "how" research questions, the comparative case study methodology is particularly effective (Yin, 2009).

1.4. Significance of the Study

The study advances knowledge about how businesses can make the transition to more sustainable and ethical practices by addressing the intersection between decommissioning and CE. The findings are meant to advance not only our theoretical understanding of this intersection but also to offer useful advice to businesses engaged in the O&G industry. A knowledge gap is filled, and new information is provided with the creation of a comprehensive practical framework that outlines the required steps for incorporating CE principles into decommissioning activities. The results of this study could be beneficial to a variety of stakeholders, such as O&G companies, regulatory bodies, environmental organisations, and local communities. In addition, this study's significance goes beyond the O&G industry itself, providing knowledge that can guide cross-industry CE practices. It is important to note that decommissioning expertise extends to comparable offshore installations like wind farms and transformer platforms rather than being restricted to offshore O&G facilities.

The adoption of circular economy principles supports the global Agenda 2030 and also makes a significant contribution to achieving the UN's Sustainable Development Goals (SDGs). The following table shows the SDGs that have been identified as particularly relevant to this research, specifying its contribution:

Table 1: Research Contribution to Sustainable Development Goals (SDGs)

SDG No.	SDG Title	Research Contribution
SDG 9	Industry, Innovation, and Infrastructure	Improving efficiency and sustainability during decommissioning develops innovative and sustainable solutions for the O&G industry.
SDG 12	Responsible Consumption and Production	Minimising waste generation and maximizing resource efficiency fosters responsible consumption and production in the O&G industry.
SDG 13	Climate Action	Integrating circular economy practices in decommissioning facilitates the reduction of greenhouse gas emissions, supporting a low-carbon economy, and enhancing climate resilience.
SDG 14	Life Below Water	Minimising the impact on aquatic environments and promoting responsible use of oceans and marine resources during decommissioning activities protects the marine ecosystems.
SDG 17	Partnership for the Goals	Achieving CE objectives in decommissioning highlights the importance of partnerships and collaboration among stakeholders (i.e., government, industry, environmental organizations).

2. Literature Review

2.1. Decommissioning

Dealing with the topic of decommissioning presents some difficulties not only because of its complexity but also because of the lack of a precise legal definition. For example, both the 1958 Geneva Convention on the Continental Shelf and the 1982 United Nations Convention on the Law of the Sea (UNCLOS) omitted the term "decommissioning" and did not specifically define it in the 1989 International Sea Act Organizational (IMO) Strategic. The 1992 Convention on the Protection of the Marine Environment of the Northeast Atlantic (OSPAR) also did not define the term. These international treaties, despite their lack of formal definitions, recognize the need to stop the use of disused coastal habitats. The term "decommissioning" became a matter of international concern in the oil industry, especially after the Brent Spar dispute in 1995 (Owen & Rice, 1999). Before this event, the idea of removing abandoned offshore platforms was commonly referred to as “abandoned”. However, the terms "abandonment" or “removal” commonly used in various documents relating to offshore installations do not extend beyond the concept of decommissioning.

2.1.1. Technical Considerations

The different structural parts of offshore platforms must be clearly defined in the context of decommissioning procedures within the oil and gas industry (Figure 1). The portion above the water's surface is referred to as the "topside." With essential components like cranes, helidecks, and drilling rigs, this topside acts as the nerve centre for offshore operations. The "jacket," a reticular structure submerged below the water's surface, was purposefully created to provide structural support to the topside while securely anchoring it to the seabed. The foundation system, the lowest and largest component of the entire offshore structure, is found further below, below the muddy layer. The stability and integrity are ensured by this foundation system. In addition to the structural components, there is a sizeable build-up of drill cuttings, which are bits of drilled rock and leftover drilling fluids left over from drilling operations carried out inside the wells. Finally, the infrastructure is completed by pipelines that are used to transport and export extracted O&G resources.

It is important to point out that the size and massiveness of these offshore installations vary significantly depending on several variables, such as water depth, and environmental conditions, as well as the degree of functionality, such as processing capacity and lodging options. Smaller installations could weigh only 200 tonnes or so, whereas larger topside structures could weigh 50,000 tonnes or more. It is noteworthy that the weight of gravity-based structures can even reach hundreds of thousands of tonnes, highlighting the complexity and diversity of offshore infrastructure used in the O&G industry (Leporini et al., 2019).

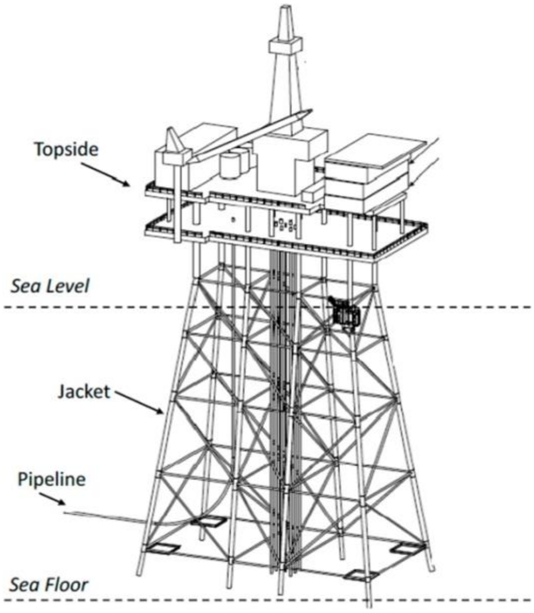

Figure 1: Typical O&G Offshore Platform (Leporini et al., 2019)

Operations switch their focus from exploration and drilling to the production phase once a commercially viable well has been found and a company complies with the necessary regulatory requirements. Engineering has made significant strides in the offshore O&G industry, making it easier to conduct drilling operations in deep and ultra-deep-water environments with high temperatures and pressures. Notably, the industry has developed a wide range of production platforms that are specifically suited to various offshore habitats (Figure 2).

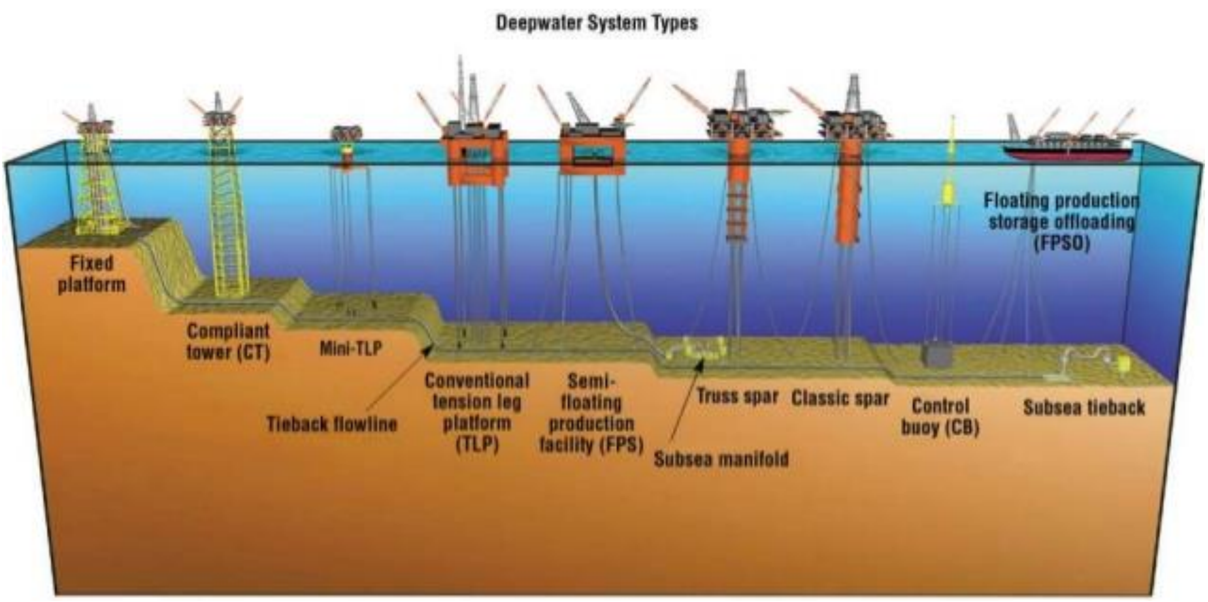

Figure 2: O&G Offshore Platform Types ('The Basics of Offshore Oil & Gas')

One popular type is the Fixed Platform (FP), which has a jacket and is a vertically towering structure made of tubular steel members and supported by piles driven into the seafloor. There are crew quarters, a drilling rig, and production facilities on the deck atop this jacket. The Compliant Tower (CT) can support a typical drilling and production deck thanks to its flexible, thin tower and piled foundation. The Tension Leg Platform (TLP), a floating structure attached to the seafloor by vertical, tensioned tendons that are fastened by piles, employs a different tactic. The Mini-Tension Leg Platform (Mini-TLP) is a specialised variation designed for the cost-effective production of smaller deep-water reserves that would be impractical to extract using conventional deep-water production systems. The SPAR Platform (SPAR) differs from other platforms in that it has a single, large-diameter vertical cylinder that supports a deck structure. SPARs typically consist of a hull secured by a taut catenary system made up of six to twenty lines anchored into the seafloor, a fixed platform topside with drilling and production equipment, three different types of risers (production, drilling, and export), and three different types of risers (export). A semi-submersible vessel with drilling and production equipment is called the Floating Production System (FPS). Either wire rope and chain are used to secure it in place or rotating thrusters are used to fix it in place. A single subsea well pumping to a nearby platform, FPS, or TLP is included in the Subsea System (SS), as well as multiple wells connected by a manifold and pipeline system pumping to a distant production facility. The Floating Production, Storage & Offloading System (FPSO) consists of a sizable tanker-like vessel tethered to the seafloor. An FPSO is used to process and store oil from nearby subsea wells and to resupply a smaller shuttle tanker on occasion. The oil is then transported by this shuttle tanker to a land-based facility for further processing (NOIA, 2021).

Decisions must be made about the future of these structures and their potential impact on marine ecosystems at a crucial juncture in the decommissioning process for offshore platforms. These options include leave in place, toppling, partial removal, and complete removal, which entails the extraction of every platform component, and the intriguing option of leaving the structure standing (Figure 3). This assessment seeks to shed light on the difficult decisions faced by stakeholders in offshore platform decommissioning by offering a thorough understanding of the processes involved in each alternative and the corresponding ecological effects. Furthermore, three different techniques can be used to disassemble platform topsides. First, the "piece small" strategy involves breaking the platform up into smaller, up to 20-ton segments. The second technique, known as the "piece large" technique, entails removing platform sections that weigh anywhere from 20 to 5000 tonnes. The third technique, known as the "single lift," entails moving the entire topside structure as a single unit (Sedlar et al., 2019).

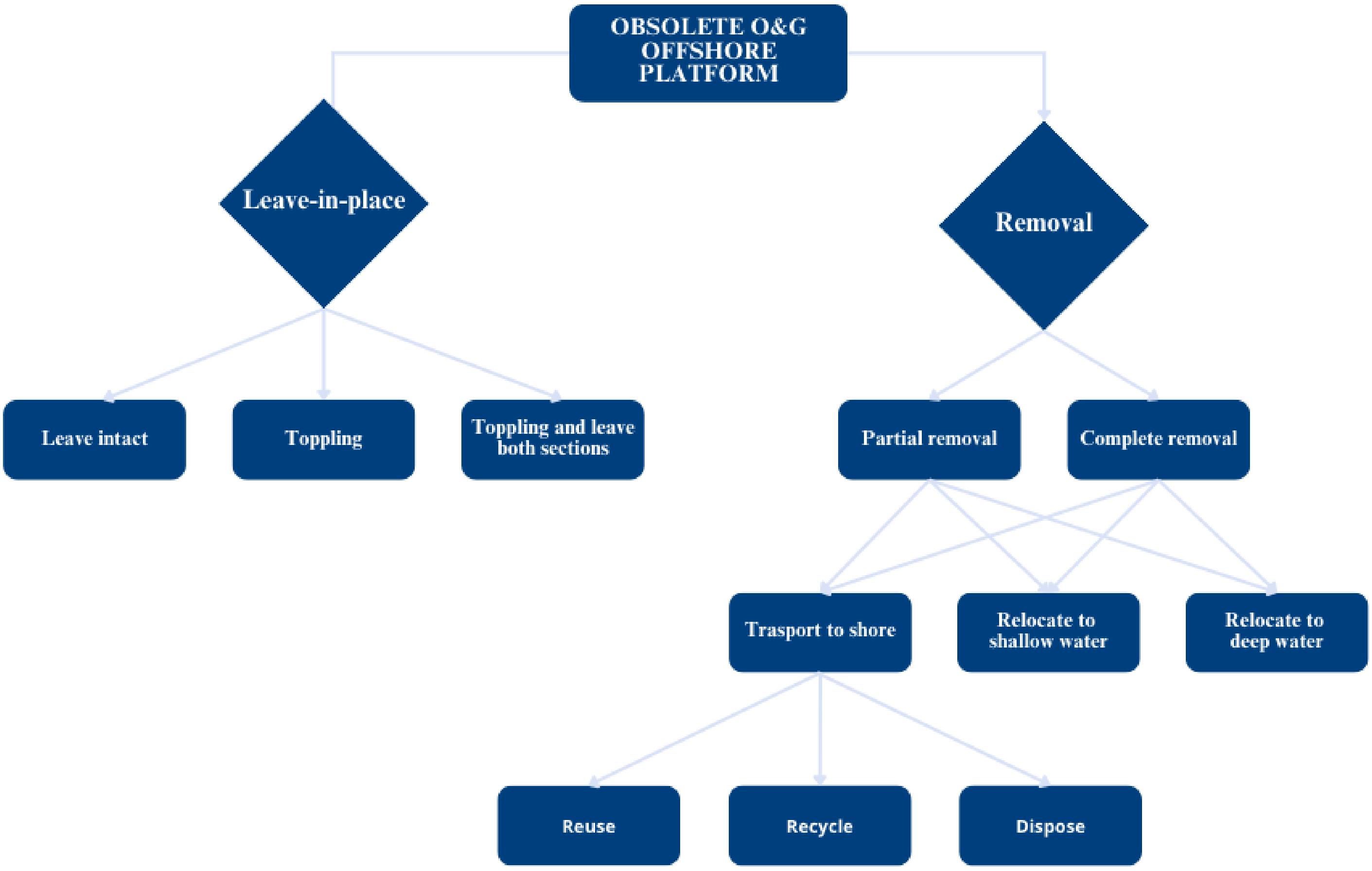

Figure 3: Decommissioning Options (adapted from Fowler et al., 2014)

2.1.2. Regulatory Framework

The Deepwater Horizon drilling rig, operated by the British energy giant BP, experienced a catastrophic explosion on April 20, 2010, which ultimately caused it to sink two days later. This was a significant incident. The Gulf of Mexico witnessed this tragic incident, which resulted in the tragic loss of 11 lives and the release of millions of litres of crude oil into the water. Surprisingly, the Deepwater Horizon oil spill ranks as the largest offshore oil spill in American history, having a devastating impact on the numerous people and communities residing in the Gulf of Mexico (R. Pallardy, 2023). This unfortunate event served as a sobering reminder of the shortcomings in regulatory oversight relating to safety, health, and environmental (SHE) safeguards, particularly in the context of offshore O&G operations. The Deepwater Horizon accident highlighted the urgent need for strict regulatory frameworks to compel industry participants to adopt sustainable practices that successfully mitigate the inherent risks associated with their operations (Wan Ahmad et al., 2016).

Decentralisation is a noteworthy trend in the field of industrial waste management law and policy. Therefore, it is necessary for local government entities to actively participate in facilitating and fostering corporate collaboration. These local organisations also play a significant role in developing tailored tools and mechanisms designed to promote collaborative waste management efforts (Costa et al., 2010). Companies and regulatory bodies must work within a strict regulatory framework to navigate the complexities of decommissioning while upholding sustainable practices. This regulatory environment governing decommissioning activities in the O&G industry is a complicated and interconnected framework made up of various international agreements, conventions, regional directives, and guidelines. It presents a significant challenge to ensure the objectivity of assessments regarding the suitability of decommissioning strategies, there is a notable absence of universally standardised procedures to guide impact assessments. Simple assessment prescription falls short in the absence of a standardised format that allows for systematic evaluation and cross-alternative comparison. Additionally, finding sustainable alternatives to decommissioning is generally not adequately taken into account by the current legal frameworks. They specifically fail to consider the feasibility of either leaving infrastructure in place or partially removing it and then reusing it as improved habitats for marine life.

Table 2:Regulatory Framework of Offshore Decommissioning

Institution	Title	Date
United Nations	The Geneva Convention on the Continental Shelf	1958
United Nations	Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (United Nations, 1972)	1972
United Nations	United Nations Convention on the Law of the Sea (UNCLOS)	1982
International Maritime Organisation	Guidelines and Standards for the Removal of Offshore Installations and Structures	1989
OSPAR	Convention for the Protection of the Marine Environment of the North-East Atlantic	1992
European Parliament	EU Offshore Directive	2013

2.1.2.1. The Geneva Convention and the UNCLOS

The Geneva Convention also referred to as the Convention on the Continental Shelf (United Nations, 1958), is a fundamental document that has important implications for the management of offshore installations. However, awareness of the decommissioning situation was still somewhat limited; real concern in this area didn't emerge until the latter part of the 1980s. Notably, it requires the complete removal of any abandoned or unused installations and emphasises the significance of providing adequate notice and a reliable warning system when building installations. Subsequently, the Geneva Convention was incorporated into the 1982 United Nations Convention on the Law of the Sea (*United Nations*, 1982). The UNCLOS shows some improvements, but it is still afflicted by unresolved issues that must be addressed for a thorough improvement of the environmental effects of decommissioning. Although UNCLOS has gradually increased its emphasis on environmental issues, the need for dismantling still primarily depends on issues relating to navigational safety. The preservation of natural habitats and fishing interests, on the other hand, do not constitute independent grounds for requiring removal. The Geneva Convention and UNCLOS thus primarily emphasise navigation-related concerns over sustainability dimensions.

2.1.2.2. The 1972 London Convention

The London Convention, also referred to as the "Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter" (United Nations, 1972), is designed to address marine pollution brought on by the dumping of waste materials into the ocean. According to that, the abandonment of offshore installations is not prohibited, but it establishes a licencing system in which explicit consent adherence to a predetermined list of materials that are deemed acceptable for disposal. Applicants are required to submit a thorough assessment outlining the potential ecological consequences that the designated materials may have on the marine environment in addition to adhering to the materials specified for permissible dumping.

2.1.2.3. IMO Guidelines

A framework for decommissioning offshore facilities is provided by the International Maritime Organization's (IMO) Guidelines and Standards for the Removal of Offshore Installations and Structures (International Maritime Organization, 1989). With a focus on safety, environmental protection, and navigation, these guidelines, which were adopted in 1989, address the complicated issues surrounding the removal of abandoned or unused installations and structures. The IMO guidelines recognise the significance of UNCLOS's Article 60, which emphasises the need to remove abandoned or unused installations to ensure navigational safety and take environmental impact into account. When making decisions about the removal of offshore installations, coastal states should take into account the requirements, factors, and standards outlined in the guidelines. Its introduction of the idea of "new use" acts as a determinant for establishing an acceptable justification for either leaving the platform in place or going through with partial removal. This notion is what qualifies these guidelines as innovative for that period. They opened the door to the possibility of reusing installations or even turning them into artificial reefs, provided that such actions do not interfere with established maritime traffic lanes. The introduction of the idea of "new use" represents a viewpoint that embraces the reusing of offshore platforms as a potential way to reduce costs associated with decommissioning activities, simultaneously protecting marine ecosystems and may even encourage their expansion and improvement.

2.1.2.4. The OSPAR Convention

The 1972 Oslo Convention for the Prevention of Marine Pollution by Dumping and the 1974 Paris Convention for the Prevention of Marine Pollution from Land-Based Sources combine to form the 1992 OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Commission, 1992). One of the strictest legal frameworks regulating decommissioning operations is undoubtedly this convention. The disposal of waste, including that coming from offshore installations, is categorically prohibited by it. The abandonment of structures on the seabed is expressly prohibited by this convention without express authorization, which is given on a case-by-case basis by the competent authority. The disposal or abandonment of offshore installations or pipelines is strictly regulated, requiring permits that meet predefined criteria, including the safeguarding of human health and the marine environment. Monitoring and inspection systems are in place to ensure compliance.

2.1.2.5. Offshore Directive of the EU

The European Union's offshore O&G operations are governed by the EU Offshore Directive (European Parliament, 2013), which has a significant impact on the decommissioning stage of these operations. The requirement that operators and owners submit several thorough documents and information to competent authorities is at the heart of its provisions. According to the Directive, companies are solely responsible for any environmental damage caused by their operational activities. Significantly, the directive requires the disclosure of details regarding independent verification plans, which are especially pertinent during decommissioning to validate the dismantling and abandonment processes and reduce risks. The exacting requirements for decommissioning documentation outlined in Annex I, which covers everything from design and relocation notifications to internal emergency response plans, emphasise how meticulously decommissioning activities are to be approached. To address the complex issues involved in decommissioning in the O&G industry, the provisions of this directive offer a thorough and structured approach that emphasizes safety, environmental responsibility, and proactive risk management.

2.1.3. Main Practices and Sustainability Impacts

Decommissioning activities have an impact on a variety of environmental factors, such as marine life, mortality, biology, marine life mortality, pollutant emission and energy consumption. The release of gas emissions is one of them that has the greatest impact. This is true in both scenarios of total and partial removal during various stages of the decommissioning process. These operations call for significant fuel consumption, mainly for diesel-powered boats, which results in the emissions of gases that can harm the environment, most notably by contributing to the greenhouse effect (Vidal et al., 2022). Structural engineers, energy experts, and project managers must work closely together to decommission these offshore assets by applying CE principles and they will all play crucial roles in ensuring operational effectiveness and safety. This can then result in the creation of high-value employment opportunities while retaining the critical knowledge needed to realise a future with lower carbon emissions (FE News, 2021). A growing body of biological evidence suggests that offshore O&G platforms provide important ecosystem services while they are operational. By deploying these platforms, a hard substrate is created in open water environments, which encourages the colonisation of different sessile organisms and leads to the creation of artificial reefs (Shinn, E. A., 1974). Due to their potential to ban some types of commercial fishing, most notably trawling, and, in some cases, recreational fishing, these platforms also have the potential to act as vital refuges for a wide variety of species (Claisse et al., 2014). The nature of decommissioning procedures in the O&G industry, especially considering the adoption of the CE, raises a significant complexity. Hence, the decision between complete removal, partial removal, toppling or leave-in-place decommissioning techniques must be made in the context of the site, with a focus on its ecological features. To choose the best course of action, comprehensive environmental impact assessments must be carried out.

2.1.3.1. Complete removal

A complete removal starts with the abandonment of wells, in which case the well bores are filled with cement. Then, either through extraction, cutting, or the use of explosives, conductors are removed from beneath the seafloor. The topsides, which contain crew quarters and machinery for processing O&G, are then extracted from the jacket. Finally, when removing the supports that are buried beneath the seabed for O&G platforms, explosives may be necessary. Explosives could be used if the pipelines are buried deeply beneath the seabed (Bull & Love, 2019). The jacket or individual pieces are then hoisted onto a cargo barge using a derrick barge for transportation. Policies supporting complete removal in the context of decommissioning procedures are based on the underlying tenet that returning the seabed to its original condition represents the most environmentally responsible course of action. Furthermore, the Brent Spar controversy was crucial in considering complete removal as the proper standard procedure for decommissioning activities. A range of environmental effects related to complete removal mainly includes the removal of safeguards for fishing grounds, the potential for contaminant dispersal, threats to endangered species, and unfavourable acoustic effects. The removal of installations poses a serious threat to the endangered species that depended on those structures, which was also widely acknowledged. Furthermore, it may be preferable to preserve chemical contamination in its undisturbed offshore state rather than run the risk of it spreading during removal activities (Fowler et al., 2018). Additionally, the noise generated during decommissioning activities has a significant negative impact on marine mammals. Specifically, the operation of vessels, underwater cutting, and other activities such as water-jetting and cutting tools cause noise pollution of above 120 dB (Shams et al., 2023). Furthermore, the complete removal option is predicted to result in an almost complete loss of associated reef biota (Claisse et al., 2015; Pondella et al., 2015). This result foretells localised declines in biodiversity in areas that are primarily made up of soft-bottom habitats. It's significant to note that the complete removal of structures opens the possibility of allowing trawling operations inside previously established safety zones. Hence, such trawling techniques have the potential to disturb drill cuttings and resuspend sediment contaminated with hazardous substances (Bakke et al., 2013). Compared to the leave-in-place option, complete and partial removal methods typically use more energy and produce more emissions. As an example, the process of tearing down and recycling the steel infrastructure of Ekofisk platforms in Norway used up the equivalent of 40% of the annual electricity consumption of a city with 100,000 people living in it (Phillips Petroleum Company Norway, 1999).

2.1.3.2. Partial removal

In this case, the conductors and topsides are dismantled along with the wells. The remaining structure, and possibly the shell mound, are left in place while a portion of the jacket is removed. Installation of navigational aids is done as needed. Topsides can be relocated to a new platform for reinstallation after cleaning, or they can be brought to shore for the recycling of valuable components, with the remaining material being dumped in landfills. In some cases, the cleaned deck's components have been reused to create artificial reefs.

The structure and makeup of related ecosystems have a significant impact on the effects of partial removal options (Ajemian et al., 2015). However, it's important to remember that partial removal options can produce better environmental results compared to complete removal when taking things like biodiversity enrichment, the creation of reef habitats, and protection from bottom trawling into account (Lakhal et al., 2009; Henrion et al., 2015). Due to their non-explosive nature, partial removal techniques have a relatively small impact on fish and invertebrate mortality, with little negative impact on marine mammals, sea turtles, and seabirds. For instance, it is predicted that partial removal in California could preserve 86% of secondary fish production and 80% of fish biomass (Claisse et al., 2015). Nevertheless, it's important to recognise that even partial removal contributes to the extinction of sessile invertebrate species and cryptic fish species found in the platform's upper sections (Shams et al., 2023). Additionally, partial removal protects the structure of the platform close to the seabed, preventing dredging operations that might disturb the build-up of shell mounds, which are composed of drilling mud and shell debris and serve as the structural support for the biological communities that exist beneath the platforms (Henrion et al., 2015). After decommissioning activities are finished, the remaining infrastructure can act as an artificial reef, sustaining a population of large fish and invertebrates that is more diverse and abundant than that found in the nearby muddy habitats (Schroeder & Love, 2004). In the Gulf of Mexico (GOM), for example, it has been used for recreational fishing (Fortune & Paterson, 2020). In addition, compared to the complete removal of the topsides of offshore O&G platforms, which can result in approximately 6.75 times more air pollution, partial decommissioning to a depth of 85 feet below the water's surface produces significantly less air pollution (Smith & Byrd, 2021).

2.1.3.3. Toppling

The abandonment of wells, removal of conductor pipes and topsides, and the choice to either remove or leave shell mounds in place are all aspects of topping that are similar to those of partial removal. The use of explosives to separate the jacket from the seabed, followed by manoeuvring it into a horizontal position and allowing it to settle on the seafloor, is what makes toppling unique. Then, if required, navigational aids are installed.

The toppling process, which frequently uses explosives, causes significant disturbances to the coral communities that live on these structures, resulting in noticeable changes to both species composition and diversity at different depths (Sammarco et al., 2014). However, it is noteworthy that a special ecological opportunity materialises because of the collapse of these platforms. A certain amount of vacant habitat is produced by the remains of these structures, which is ideal for the colonisation of a wide variety of species. Indeed, the toppled platform structure effectively acts as a newly formed artificial reef in this situation (Schroeder & Love, 2004).

2.1.3.4. Leave in Place

The platform and the associated shell mound remain in their original locations after decommissioning under the no-removal option. Navigational aids are mounted, and the topside is stripped and cleaned. The no-removal option allows the platform and shell mound to continue operating as they did before the decommissioning with little to no effects on local marine populations. Certainly, the operational activities result in complete and partial removal strategies typically involving higher levels of direct energy consumption and emissions (Schroeder & Love, 2004). Indeed, the leave-in-place approach offers an alternative decommissioning method for the O&G industry that leaves the platform and associated shell mounds undisturbed and maintains their original functionality. This strategy has very little to no negative effects on regional marine populations. The "leave-in-place" option has the potential to turn the platforms into thriving habitats with significant soft sediment environments. Fish and invertebrate species that might not otherwise be able to colonise an area are now able to do so thanks to this adaptation (Sommer et al., 2019). This option presents several benefits, including the ability to create artificial reef habitats, which have been shown to increase marine biomass and biodiversity (Day et al., 2018). This decommissioning method also does away with the need for expensive, labour-intensive platform dismantling. Instead, these buildings are allowed to age naturally over time, which nevertheless contributes to some air pollution. In contrast to other decommissioning techniques, the environmental impact in terms of pollution is significantly lower with this method (Shams et al., 2023).

2.2. Circular Economy Principles and Practices

Despite being conceptualised earlier, the term "circular economy" was first used in writing in 1990 (David W. Pearce & R. Kerry Turner, 1990). Kirchherr et al. (2017) have provided a comprehensive analysis of 114 definitions of the CE, highlighting the diverse perspectives and conceptualizations within the literature. The analysis reveals common themes such as resource efficiency, closed-loop systems, and waste reduction. These variations in terminology and scope indicate the evolving nature of the concept and the need for further clarification and standardization. However, the description of the CE which provides a common thread among these definitions is an "*economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro-level (products, companies, consumers), meso level (eco-industrial parks) and macro-level (city, region, nation and beyond), to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity, and social equity to the benefit of current and future generations. It is enabled by novel business models and responsible consumers*." (Kirchherr et al., 2017).

Several factors have contributed to the growing interest in the adoption of the CE. The Ellen MacArthur Foundation (2013) outlines the economic and business rationale for transitioning to a CE, highlighting the potential for cost savings, innovation, and job creation. In addition, a need is emerging for a balanced interplay between environmental and economic systems, suggesting that the CE offers a sustainable pathway for achieving this balance (Ghisellini et al., 2016). The European Commission (2020) has recognized the CE as a key policy agenda for a cleaner and more competitive Europe, emphasizing the potential for achieving environmental objectives while stimulating economic growth and enhancing Europe's global position. The concept of the CE is an alternative to the linear model that focuses on reducing waste generation and optimizing resource flows (Stahel, 2016). It differs from traditional linear economic models in emphasising the valuation of materials within a closed-looped system to allow for natural resource use while reducing pollution or avoiding resource constraints and sustaining economic growth. It represents a new sustainability paradigm that shifts from the "take-make-dispose" approach to one that prioritizes resource efficiency, ecosystem preservation, and social well-being (Geissdoerfer et al., 2017). This paradigm recognises the interconnectedness of environmental and economic systems and emphasizes the potential for positive synergies between the two. Companies have a big chance to align their vision with sustainability goals thanks to the CE, which successfully combines economic, environmental, and social objectives (D'Amato et al., 2017). In particular, the literature has demonstrated that environmental management practice takes to long-term economic viability. However, given that for implementing all the CE activities substantial initial investments are required (Liu & Bai, 2014), they benefit mainly patient businesses in terms of financial rewards (Gotschol et al., 2014). It is critical that a lack of social and environmental commitment can harm a brand's reputation and sales (Seuring & Müller, 2008). As a result, businesses are more likely to support green and circular initiatives to solidify their position as proponents of "ethical leadership" and improve their reputation (Bressanelli et al., 2019). This tendency is especially important when it comes to the O&G industry, which historically hasn't had a thorough sustainability perspective (Shqairat & Sundarakani, 2018). Environmental cooperation is crucial to encourage environmentally friendly production methods. Managers and practitioners have to actively look for ways to collaborate with supply chain partners to achieve an integrated supply chain to maximise sustainability benefits (Gotschol et al., 2014).

Businesses must overcome a wide range of difficulties due to the complexity and multifaceted aspects of the transition to adopting CE practices. Notable barriers to the adoption of the CE primarily have a cultural basis. These cultural barriers include low consumer awareness and engagement levels as well as a cautious organisational culture. These market-related barriers, which primarily result from the lack of coordinated governmental interventions aimed at accelerating the transition to circular economic models, in turn, aggravate these cultural barriers (Kirchherr et al., 2018). The integration of circular business models within the larger value chain context has been hampered by investments in pre-existing manufacturing facilities and value chain configurations. Some businesses expressed concern that the implementation of novel circular systems might cause a shift in business away from established and successful setups. It is stressed that significant resources, such as time, money, and significant efforts, have already been devoted to the development of these existing infrastructures (Guldmann & Huulgaard, 2020). In addition, it can be challenging to define new value propositions consistent with the principles of the CE and to identify the right circular business models due to the uncertainty surrounding structural adaptation (Lahti et al., 2018). Moreover, the establishment of reverse value chain activities presents another considerable challenge. Reverse value chain activities, such as product returns, that span all firm activities and necessitate significant changes in the entire value chain, take time for businesses to establish and organise. Occasionally, consumers are given incentive mechanisms in the form of rewards, fidelity points, and/or discounts on future purchases, all of which are very successful at enhancing, consolidating, and integrating CE systems by encouraging their involvement in the reverse value chain (De Giovanni, 2022). In addition, in comparison to a simple logistics strategy for delivering goods to the final consumer, a logistics strategy that also takes into account reverse flows dealing with CE practices is much more complex, implying a longer lead time, a lower level of service, and higher logistics costs (Salandri et al., 2022). However, since the product remains in the manufacturer's control throughout its entire life cycle, this barrier is not present in the CE system of the O&G facilities decommissioning.

2.2.1. Circular Economy 3 R's Framework

A fundamental framework for the circular economy implementation revolves around the so-called "3R" principles, namely the strategies of reducing, reusing, and recycling (Liu et al., 2017). They represent the three main pillars of the waste management pyramid. Followed by reuse and recycling, reduction is the ultimate goal of CE, which aims to use as little material as possible during product design (Carter & Ellram, 1998). There are significant and beneficial effects of practices for recycling, reducing, and reusing on operational performance (Salandri et al., 2022). The 3R principles are aligned with strategies aimed at resource procurement, landfill reduction, and greenhouse gas emissions mitigation, considering the management of hazardous waste as a crucial factor in achieving resource circulation (Sakai et al., 2011).

Figure 4 provides a concise narrative of the transition to a CE paradigm. It underscores the transformative potential of adopting CE practices which extend the lifespan of products. The disposal paradigm represents the conventional linear endpoint with the lowest value contribution, while reduce and reuse ones represent the best practices of circularity, offering the highest value through resource efficiency. In addition, while recycling and energy recovery are integral components of the CE paradigm, their placement in the waste cascade signifies their lower value. Indeed, the complexities and limitations associated with recycling and energy recovery processes, including potential material quality degradation and environmental impacts, necessitate a balanced approach that prioritizes reducing and reusing products before applying these intermediate-value practices.

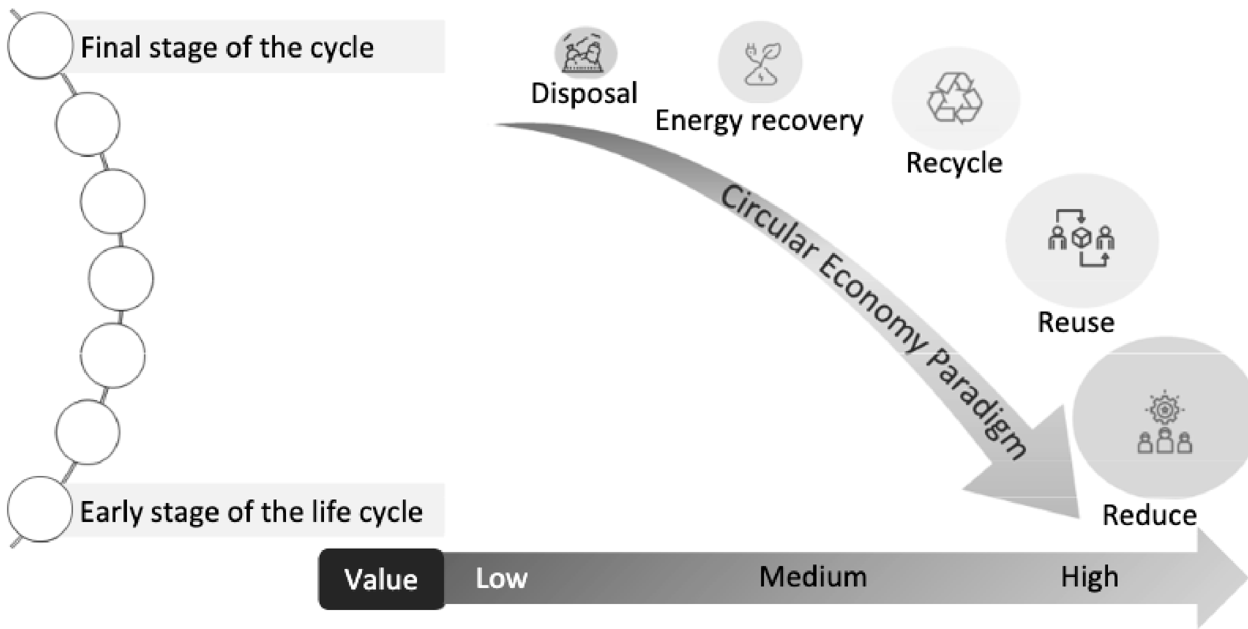

Figure 4: The waste cascade (De Giovanni & Folgiero, 2023)

Similarly, the concept of the CE, as shown in Figure 5, is that of a system that is made up of a series of concentric loops. The internal loops of this framework hold the most potential for resource preservation and value creation. While recycling is seen as a significant but secondary activity in the model, priority is given to minimising resource input through the reducing principle, and then reusing them to keep the most of them within the economy. (Green Alliance, 2021). In addition, as per an impact assessment within the literature that presents the environmental burdens and savings per kg of waste in terms of resource consumption for each scenario, in the case of both open-loop and closed-loop recycling the net balance of environmental burdens versus savings showed that closed-loop recycling is more resource efficient than energy from waste scenario. However, the closed-loop recycling showed a lower loss of resources than the open-loop practice (Huysman et al., 2015).

The emphasis on reduction in this model implies that industrial processes should strive for greater efficiency, producing more significant results with fewer resources. The adoption of innovative business models and improved product designs simultaneously makes it easier to reuse products. This approach to resource management has the potential to cut down on waste production and material consumption by half. A significant reduction in carbon emissions, pollution, and the negative effects of resource extraction are all outcomes of such a scenario, which is crucial for environmental conservation.

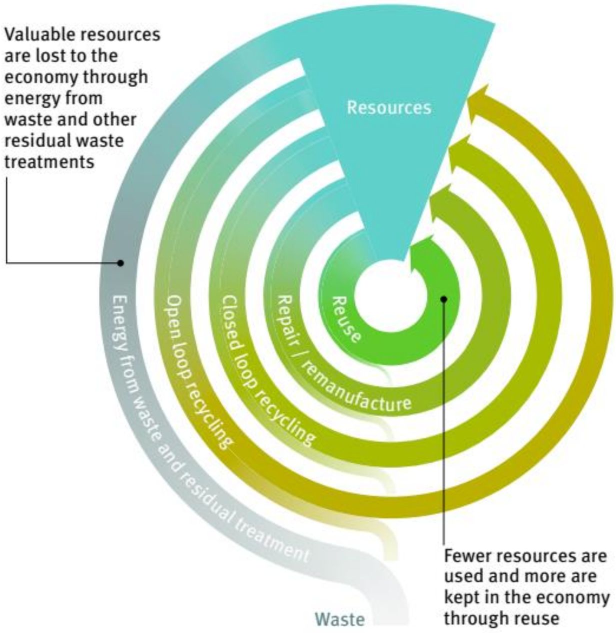

Figure 5: Circular Economy loops (Peake & Brandmayr, 2019)

2.2.1.1. Reducing

The CE paradigm's concept of reduction takes many different forms in real-world contexts, primarily aiming to do away with the need for material recycling or reusing. The main objective of the reduction principle is to use as few resources as possible, minimising the use of virgin raw materials while simultaneously utilising the residual value obtained in waste and returns (De Giovanni & Folgiero, 2023). A reduction-focused strategy includes improving the utilisation of materials and resources, including energy efficiency, both during the design process and throughout the product lifecycle (Potting et al., 2017). This idea is in line with the eco-design philosophy, which plays a crucial part in the CE framework and enhances its benefits, especially those related to resource utilisation. Eco-efficiency captures the essence of the "doing more with less" logic by achieving more with fewer resources (McDonough & Braungart, 2010). With the ultimate goal of completely negating or drastically reducing the need for reusing or recycling materials, eco-design's primary goal is to reduce all environmental footprints throughout a product's lifecycle (Prendeville & Sherry, 2014). The configuration and management of the entire value chain are significantly impacted by a product's characteristics (Bevilacqua et al., 2008), highlighting the critical role of design in enabling closed-loop supply chains and cooperative ownership models with a focus on sustainability (Souza, 2013).

2.2.1.2. Reusing

The principle of reuse, as defined by the EU Commission, refers to "any operation by which products or components that are not waste are used again for the same purpose for which they were conceived" (EU Waste Directive, 2018). With the overarching goal of extending the product's lifecycle, specific product components can be easily used within the framework of the CE to create either new products or refurbished items (De Giovanni & Folgiero, 2023). This concept is inherently interesting from an environmental standpoint, mainly because it uses fewer resources, less energy, and less labour than manufacturing new things from scratch or even recycling and disposal procedures. Additionally, implementing reuse practices has the potential to improve certain population segments' quality of life as well as local economies' competitiveness and environmental effects (Castellani et al., 2015).

2.2.1.3. Recycling

According to the EU Waste Directive, the recycling principle refers to "any recovery operation by which waste materials are reprocessed into products, materials, or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations" (EU Waste Directive, 2018). Recycling is consistent with the idea of recovering materials from waste streams and reintegrating them into production processes to restore a product's original characteristics or use them in alternative applications (De Giovanni & Folgiero, 2023). Recycling waste materials offers the chance to utilise still-useful resources while also lowering the amount of waste that needs to be treated or disposed of, thereby reducing the associated environmental effects (Birat, 2015).

Although recycling is frequently linked to the CE, it is important to stress that recycling may not always be the most sustainable option when compared to other aspects of the CE, like reduction and reuse, especially when looking at resource efficiency and financial viability (EU Commission, 2023). As a point is reached where additional recycling becomes environmentally or economically impractical, the benefits of recycling tend to decrease. Because some materials have limited recycling lifecycles, it is frequently impossible to achieve 100 per cent recycling (Andersen, 2007). However, contrary to materials like cellulose fibres, which have a low potential for recycling, metals can be recycled indefinitely (Reh, 2013). Hence, in the context of CE practices in the O&G decommissioning industry, where metal materials, particularly stainless steel, are widely available, this aspect is extremely relevant. Indeed, the Hewett installations owned by ENI count 89.5% of ferrous metal material in their estimated inventory (ENI, 2021).

2.3. The Intersection of Decommissioning and Circular Economy

The circular economy's potential benefits have recently gained more recognition in the oil and gas industry. Comparing CE strategies to others that involve the simple disposal of such infrastructure, they have the potential to offer significantly increased ecological value (Ajemian et al., 2015). After production stops, abandoned offshore rigs may have negative effects on the environment, such as the release of contaminants due to rig corrosion, changes to natural food webs, and an increase in the populations of invasive species (Macreadie et al., 2011). The circularity approach aims to improve resource efficiency, extend resource utilisation, and reduce waste within the complex landscape of platform end-of-life activities management. The O&G industry can rely on a well-established practice of recycling materials. Now, recycling materials – exemplified by a recycling rate of over 90% – remains the most relevant sustainable waste management method. Nevertheless, it is worth mentioning that recycling emerges as the main contributor to the greenhouse warming potential (GWP) of decommissioning activities due to its energy-intensive processes. This involves several energy-consuming steps, including material pre-processing, transportation, and smelting (Reck & Graedel, 2012). The leave-in-place approach and reusing structures have greater value than recycling them (Capobianco et al., 2022). The potential for reuse in accordance with the current modules and equipment typically ranges between 10% and 15% of the total inventory of the materials (Decom North Sea, 2015). Therefore, to maximise value extraction, the barriers to reuse should be removed. Increasing decommissioning operations' efficiency and implementing a radical change in waste management could cut greenhouse gas emissions while also saving money.

A notable lack of knowledge, instruction, and comprehension of CE principles has prevented the O&G industry from adopting CE practices on a large scale (Sharma et al., 2023). According to a study by Lindauere et al. (2020), the shift from a paradigm that emphasises recycling to one that emphasises the reuse of materials is a complex process that is threatened by significant difficulties. Several crucial factors emerge around technical challenges. First and foremost, it is crucial to make sure that reused equipment achieves and maintains a level of reliability, effectiveness, and functionality comparable to that of newly acquired equipment. The second challenge is navigating the complexities of compliance with evolving regulatory frameworks. Thirdly, it becomes crucial to conduct an assessment of the financial costs involved in reconditioning and recertifying equipment.

Furthermore, it is needed to deal with potential increases in maintenance costs, as well as costs of moving equipment to a new operational location. Lastly, care should be taken to make sure that reused equipment fits with the receiving facility. On the other hand, legal and administrative obstacles simultaneously create their own unique set of problems, such as the allocation of working interests regarding the assets, the perimeter surrounding legal liability about reused materials or equipment, tracking potential material stock depreciation and, lastly, taking into consideration the short-term storage during the phases of materials transition.

Although it is feasible to apply CE principles to the decommissioning of existing infrastructures, it is easier to optimise costs and benefits when these ideas are ingrained as fundamental guiding principles during the asset's design and construction phase, taking into consideration the CE reduction principle (Invernizzi et al., 2020). A three-stage strategy has been proposed for implementing a CE approach to the decommissioning of O&G rigs in the North Sea. The first aspect entails working with operators to lead the transition toward a CE. The second aspect concentrates on creating a market for end-of-life decommissioning, and the third one focuses on the initial stages and end-of-life phases of a rig's life cycle. It takes to reach significant synergies including the reduction of net decommissioning costs, the development of new subsectors within the O&G industry, and the mitigation of environmental effects related to material recycling and disposal. In a scenario with lower oil prices, these sub-sectors might present more market opportunities and help create jobs (The RSA Great Recovery, 2015). Stakeholder pressure is the main factor influencing the achievement of sustainable supply chain objectives in the O&G industry, both strategically and operationally. Companies can take a proactive approach to managing this pressure by identifying relevant stakeholder cohorts at the project's outset who may have an impact on or be affected by their supply chain decisions and operations. This early involvement gives businesses the ability to anticipate stakeholder expectations and concerns, which facilitates the creation of specific strategies to address them (Wan Ahmad et al., 2016). It is essential to involve a group of public and private partners who work together within a connected network to promote development and achieve scalability to support the sustainable management of offshore platforms (Basile et al., 2021). This network can make it easier to exchange the knowledge, tools, and materials needed to effectively apply the principles of the CE. Collaboration across a range of disciplines, including engineering, economics, social sciences, and policy-making, is required to tackle the multifaceted challenge of adopting the CE in O&G decommissioning. Therefore, the legal framework must be flexible and adaptable (Techera & Chandler, 2015).

An in-depth analysis of the literature regarding the scenarios involving the CE's reusing principle of offshore O&G platforms has been done in the following table:

Table 3: Circular Economy Reuse of Offshore Oil and Gas Platforms' Scenarios

Reuse Scenario	Contribution	References
Offshore Wind Turbines	An offshore platform at its end-of-life stage could serve as a support structure for a wind turbine, this may entail retrofitting a platform for relocation to a wind farm site.	(Kaiser et al., 2011)

	As an alternative, platforms could be left in their current locations and have wind turbines added to the tops of their deck structures. Platforms can also be used to support independent wind turbines nearby by acting as centralised electrical service platforms	
	Reusing pipelines is a crucial factor to take into account in these endeavours because it has a positive impact on decommissioning costs and environmental sustainability in addition to capital expenditure (CapEx) and levelized cost of energy (LCoE) for renewable energy projects	(Mahmoud et al., 2021)
	The significant CapEx discount rates linked to wind power projects that offset decommissioning must be highlighted. These initiatives also have notable socio-economic advantages and lower carbon emissions, particularly through the reuse of offshore oil and gas infrastructure.	(Braga et al., 2022)
Carbon Capture Utilisation and Storage (CCUS)	Due to their proven track record of safe and long-lasting storage capabilities, supported by extensive geological data gathered throughout their operational lifespans, depleted gas fields offer a distinct advantage for reusing them for Carbon Capture and Storage (CCS) initiatives. The opportunity to strategically reuse offshore infrastructure elements, such as pipelines, platforms, and well facilities, is significant. It strategically delays the costs associated with decommissioning activities while also reducing up-front CapEx. This scenario also makes it easier to quickly implement CCS initiatives on a large scale.	Luna-Ortiz, 2022
	Given that a sizeable portion of the necessary CCS infrastructure already exist, the reusing of wells and fields for CO2 injection provides the advantages of potential cost savings and a reduction in the time requirements of its development.	Hoskin & Heller, 2023
	Through survival analysis, an analytical tool capable of examining the potential of pipeline reuse based on historical failure records, has provided approximations of remaining operational lifespans when compared with conventional feasibility assessments. This analysis has produced empirical data showing that several kinds of pipeline systems can operate safely for longer than their originally planned operational life cycle.	Mahmoud & Dodds, 2022
	The availability of pre-existing pipelines that can be converted to transport CO2 provides CCS initiatives with tangible economic benefits. This recognition underlines the fact that, when the costs of multiple CCS projects are shared, capital expenditures related to transport infrastructure make up a relatively insignificant portion of total expenditures, typically ranging from 10% to 20%.	Brownsort et al., 2016
Hydrogen Synthesis	Green hydrogen (H2) produced from renewable resources becomes a key component of the overall decarbonization effort. Notably, the Hydrogen Offshore Production (HOP) project, which offers opportunities for the reuse of offshore infrastructure while simultaneously addressing the necessity of establishing a low-carbon energy supply on a national scale, has shed light on an alternative pathway to decommissioning. This project has proven that various decentralised hydrogen generation, storage, and distribution mechanisms are feasible and can be combined to produce scalable offshore hydrogen. Additionally, it serves a second purpose of partially offsetting the decommissioning-related costs that currently hang over all offshore assets and infrastructure.	Pearson et al., 2019

	The technical viability of using offshore platforms, connecting pipelines, and exhausted reservoirs for the generation and storage of hydrogen (H2) has recently been assessed, with reference to the Italian context. In the ongoing exploration of circular economy practices within the O&G decommissioning, this approach represents a sizeable economic opportunity.	Carpignano et al., 2023
Artificial Reefs	"Rigs-to-Reefs" refers to a potential outcome in the decommissioning of offshore oil and gas structures in which outdated infrastructure is used as artificial reefs rather than being brought back to shore for disposal.	Kaiser & Pulsipher, 2005
	Various marine organisms are accommodated on these standing platforms, enabling sustainable growth and eventual harvest.	Kolian et al., 2018
	"Rigs-to-Reefs" initiatives date back to the 1980s when abandoned platforms from Louisiana were moved to Florida and transformed into artificial reefs.	J∅rgensen, 2009
	When choosing the "Rigs-to-Reefs" option, assessments must be made regarding the potential spread of marine invasive species during the transfer of rigs from shallow to deep waters. Reusing pre-existing jacket structures as artificial reefs is an environmentally responsible and sustainable method of decommissioning	Rotelli et al., 2017
	An intriguing project in Malaysia shows how a jack-up oil rig can be converted into a diving and marine exploration facility that caters to people interested in having an immersive marine experience.	Getech Group plc, 2021

These studies shed light on the potential benefits and challenges associated with reusing offshore assets for alternative purposes. However, a significant gap in the literature becomes evident. Notably, none of the existing studies are based on completed and past decommissioning projects within the offshore O&G industry. While literature discusses the possibilities of reusing infrastructure, the practical integration of CE principles in the decommissioning of offshore O&G facilities remains relatively unexplored. This gap is particularly noteworthy because it presents a unique opportunity to investigate how recycling and reusing principles of the CE have been practically implemented in real decommissioning scenarios. Hence, the first research question for this research is the following:

- *RQ_1: How are the principles of the circular economy, specifically recycling, and reusing, manifested and integrated into oil and gas offshore decommissioning processes?*

RQ_1 serves as a foundational exploration, aiming to provide insights into how CE principles have been applied in decommissioning through the analysis of past projects. Therefore, based on the findings from RQ_1, the following research question has been established to build upon the knowledge gained and provide actionable guidance where the emphasis shifts towards devising actionable strategies for current and future decommissioning activities:

- *RQ_2: How can the offshore decommissioning activities in the oil and gas industry effectively incorporate circular economy practices?*

3. Methodology

3.1.1. Comparative Case Study

With a focus on the Close-out Reports, the comparative case study analyses five completed decommissioning projects in the oil and gas industry. The Close-out Report provide an ex-post decommissioning analysis, specifying how the decommissioning process was carried out, describing what was accomplished and how closely it adhered to the original plan. For answering "how" research questions, the comparative case study methodology is particularly effective (Yin, 2009).

The sole source for all the case studies in this study is the official UK Government website. This database acts as the distinctive and reliable resource that has been adopted for our research. It offers a wealth of useful information, including decommissioning programmes, exact dates, locations, specifics of decommissioned installations, decommissioning techniques, and close-out reports when available. Therefore, all the selected case studies are located in the UK Continental Shelf (UKCS).

Case selection has been firstly made based on the reports available. In particular, at the date of this research, there were 30 approved decommissioning programmes of which a Close-out report was available. The range of approved dates of these reports was 2011-2023. They have been carefully analysed to select those that showed a relevant alignment with the CE practices in their project, particularly referring to the reuse principle which often is completely lacking. The following table shows the selected case studies:

Field	Operator at Decommissioning Programme approval	Operator at Close-out report approval	Date of Close-out report acceptance
Leadon	Maersk Oil North Sea UK Limited	TotalEnergies E&P UK Limited	February 2023
Renee & Rubie	Endeavour Energy UK Limited	-	September 2021
Schiehallion & Loyal	Britoil Limited	-	May 2019
Rose	Centrica Resources Limited	-	October 2018
Shelley	Premier Oil	-	February 2012

Each case study analysis includes a high-level overview that includes all of the pertinent information regarding its location, historical context, and the assets involved. The decommissioning procedures used in each case are then highlighted, describing whether platform structures were completely removed, partially removed, or left in place. Additionally, the analysis examines how each project adheres to the principles of the circular economy, with a focus on efforts to reuse and recycle waste, which ratios have been shown.

3.1.2. Interview

A structured interview has been designed to obtain detailed information and insights on the following key areas:

1. Resistance to change in the O&G industry;
2. Regulatory framework for offshore decommissioning;
3. Lifecycle management of offshore platforms;
4. CE practices in decommissioning; and
5. Synergies with offshore wind energy.

The interviewee has been selected based on his qualifications and extensive experience in the O&G industry, particularly in offshore drilling and decommissioning holds over 13 years of experience as an Offshore Drilling Assets Engineer at a registered contractor in Italy. This contractor operates a diverse fleet of drilling assets capable of functioning at various water depths, from shallow to ultra-deep waters. Additionally, the company is actively involved in decommissioning activities and has completed more than 30 decommissioning projects worldwide, including environmentally responsible projects in Scotland where up to 97% of the structure was recycled.

Interview responses have been recorded, transcribed, and subjected to qualitative analysis. This analysis involves identifying recurring themes, extracting meaningful insights, and relating them to the research objectives. The findings from these interviews will be presented and discussed in the "Discussion” section of this research. Additionally, a precise transcript of the interview, including the exact questions, has been presented in the “Appendix” section. To facilitate effective communication with the interviewee, the interviews were conducted in Italian, the interviewee's native language. Subsequently, the interview transcript will be translated into English to ensure clarity and consistency in the presentation of the data within this research study.

4. Case Studies

4.1. Leadon Field (Maersk Oil, 2022)

4.1.1. Overview

The Leadon Field, which was discovered in 1979, was installed in 1998 after an appraisal well was drilled there, and production there commenced in 2001. In 2004, a CoP request was made. The two drill centres, A and B, of the field contained a total of 18 wells. In Drill Centre A, there were seven production wells, one water injector, and one suspended well; in Drill Centre B, there were three production wells, one water injector, one aquifer well, and four suspended wells. A mid-line structure close to the location of the FPSO centre was connected to the field's infrastructure using bundle sections of 42.5 inches and 47.5 inches.

4.1.2. Decommissioning Solutions

The approach differs for various components of the O&G facility. The GP3 FPSO, removed with moorings in 2006 and redeployed to the Donan Field, represents a commendable example of reuse within decommissioning. In the case of subsea installations, the inclusion of wellhead protection frames integrated into the tree structure and their subsequent removal with the Christmas Trees in December 2019 illustrates a strategy that emphasizes efficiency and resource conservation. Riser bases recovered to shore in July 2017 were disposed of or recycled. The approach taken for pipelines, flowlines, and umbilicals shows a mixed strategy. Some elements have been left in place and others were recovered and disposed of/recycled. The removal of all mattresses using remotely operated vehicles (ROVSV) demonstrates a commitment to responsible waste management. The identification of only two failures during recovery and the subsequent recovery of these components in their parts further highlight the sustainable approach taken. The practice of permanently plugging and abandoning (P&A) all wells is a responsible approach, aligning with environmental protection goals. Drill cuttings left undisturbed on the seabed to degrade naturally is in line with the principle of minimal intervention.

4.1.3. Circular Economy Practices

The vessel's suitability for re-use aligned with the circular economy's "Reuse" principle, as well as the reuse of the FPSO. Specifically, the decommissioning solution involved moving the FPSO to the Donan Field on the UKCS in 2006 after disconnecting it from the Leadon Field. This choice was made following Leadon Field's terms of CoP, which took effect on January 1st, 2005. Therefore, whereas production started in 2001, the rational reuse is mainly due to the few production cycles of the asset. Additionally, the subsea installations have all been recycled onshore, together with the mattresses and the part of pipelines removed.

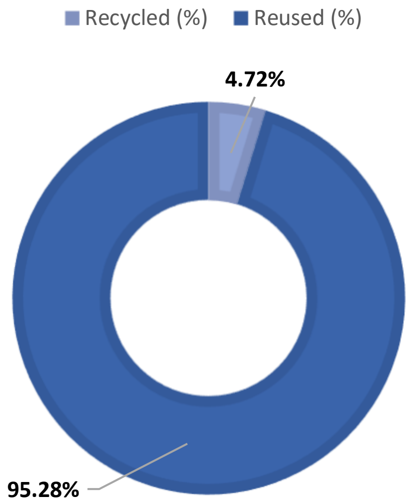

Figure 6: Leadon's Recycled and Reused rates of removed material.

4.2. Schiehallion And Loyal Fields (Britoil Limited, 2018)

4.2.1. Overview

The Schiehallion and Loyal Fields have been significant contributors to the oil and gas production landscape. These fields have operated in water depths ranging from 300 to 550 metres; they are situated about 130 kilometres west of Shetland and 35 kilometres east of the Faroese-UK border. The infrastructure at Schiehallion and Loyal consists of an extensive subsea network, the FPSO, five drill centres with 54 wells each, and a gas export pipeline that connects to the Sullom Voe Oil Terminal in the Shetland Islands. Shuttle tankers are used to export the oil from these fields. The production took place during the years from 1998 to 2013, until the FPSO experienced declining operational efficiency over time and was unable to meet future production demands, despite the substantial reserves that remain in these reservoirs. The fields are being redeveloped as part of "Project Quad 204" to address this issue. The Quad 204 Project will extend the life of the two fields, enabling them to continue production beyond 2035. This redevelopment effort entails the deployment of a newly built FPSO vessel, the addition of new wells, and the expansion of the subsea infrastructure. Reusing existing facilities whenever possible is still a top priority, but some parts need to be disconnected, isolated, and left in situ for possible future use.

4.2.2. Decommissioning Solutions

The FPSO's removal from the field was required by the decommissioning strategy chosen, which involved towing the FPSO and making the necessary preparations to make its future deployment easier. The decommissioning of pipelines, flowlines, and umbilicals presents a dual approach, divided into reusing and leaving in place.

4.2.3. Circular Economy Practices

The current FPSO was chosen for removal to make it ready for sale and reuse after being determined to be unfit for long-term field production. The Schiehallion FPSO departed the field in 2014 and was towed to Rotterdam, Netherlands where the completion of the sale to Bumi Armada occurred based on refurbishment and redeployment under a new operatorship. The pipelines, flowlines, and umbilical have been taken into consideration for the Quad 204 Project for either reuse or leave in place. Specifically, 85 items have been recovered to return to service in the refurbished field, while 21 have been suspended and left in place, together with the drill cuttings have been left undisturbed on the seabed. A variety of factors are considered during this decision-making process, including the interests of other marine users, the potential for future hydrocarbon developments, the impact on the environment, the material deterioration, and the individual circumstances of each decision-maker. The ultimate objective was to use existing infrastructure as efficiently as possible while preventing environmental harm. Excluding the FPSO sale, 4482.54 Te of material has been recovered from the seabed (excluding moorings). Of this, approximately 526 Te have been reused, 3812Te have been recycled, and 131Te have been sent to landfill.

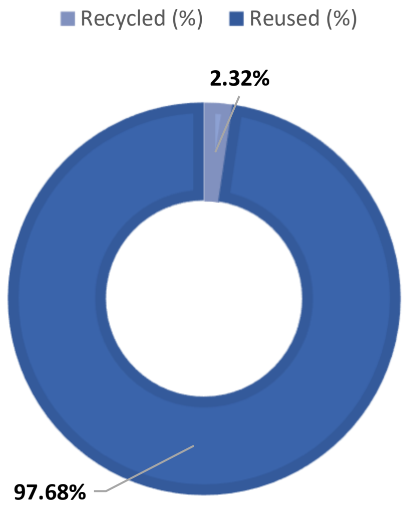

Figure 7: Schiehallion and Loyal's Recycled and Reused rates of removed material.

4.3. Shelley Field (Premier Oil, 2012)

4.3.1. Overview

A small-scale oil field nearing the end of its economic viability is the Shelley Field, which is situated roughly 192 kilometres off the northeast coast of Scotland in the central North Sea. Since production began in August 2009, the performance of the Shelley wells has not meet expectations. The reservoir pressure fell significantly and the proportion of water in produced fluids rose much quicker than anticipated. The field quickly became sub-economic so Premier sought CoP in July 2010. Except for the production pipeline, this decommissioning project demands the removal of all infrastructure and facilities from the seabed. The field consists of two producing wells connected by jumpers, a subsea manifold, and a production pipeline that spans a distance of 2 kilometres. The operational centre for the Shelley wells is the FPSO Sevan Voyageur, which is moored by twelve anchors and connected by a 2.42-kilometer trenched electro/hydraulic control umbilical.

4.3.2. Decommissioning Solutions

Flushing will be done to get rid of hydrocarbons before decommissioning operations start on the wells, wellheads, jumpers, manifolds, and production pipelines. Except for brief exposed sections, the pipeline stayed in its trench, shielded by an existing layer of rock dust. The umbilical cord's hydraulic fluids and chemicals have been flushed and returned for proper disposal. Without releasing any chemicals, hydrocarbons, or solid waste into the ocean, the FPSO Sevan Voyageur has been depressurized and made secure for relocation. Importantly, a comparative assessment has been done to determine the best decommissioning options for the pipeline and umbilical, focusing on factors like safety, cost, technical viability, environmental impact, and CO2 emissions.

4.3.3. Circular Economy Practices

Once onshore, the riser, buoyancy modules and clump weights were sold to third parties for re-use and the multiphase flowmeters and SCM were removed from the manifold and shipped back to the vendor for safe disposal of the radioactive sources and general refurbishment. The manifold remains stored in the UK, awaiting a re-use opportunity by Premier or a third party. The recovered concrete mats were re-used as foundations by a third party, while the recovered sections of the production pipeline, ballast blocks and roof panels were disposed of responsibly. It is noteworthy that 550 Tonnes of construction materials have been reused and only 35 have been recycled. Later, it was confirmed that the FPSO would be refurbished and redeployed on the Huntington field in 2012. Additionally, a thorough examination of operational equipment revealed 296 items that could potentially be reused, with an emphasis on the oil and gas industry. According to the proposed programme, 98.1% (by mass) of the materials currently in use have been reused, demonstrating a commendable commitment to circularity. The seabed regions that the FPSO and the drill centre had previously occupied can now be used for fishing, which will have a positive effect on regional fisheries. The manifold, jumpers, and wellhead, among other essential subsea infrastructure parts, can be restored and reused, which reduces waste production and helps preserve resources.

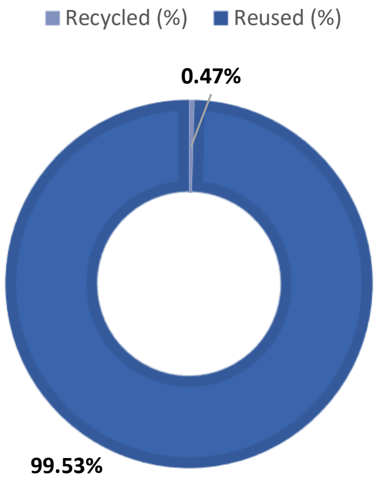

Figure 8: Shelley's Recycled and Reused rates of removed material.

4.4.Renee and Rubie Fields (Hess, 2021)

4.4.1. Overview

The Rubie and Renee fields are owned by HESS Services UK Limited (HESS). Production from the fields started in 1999 and ceased in 2009, and the decommissioning program was initiated following approval in 2014. HESS became the operator in 2018, with Petrofac Facilities Management Limited (Petrofac) also appointed as an operator in 2019. Decommissioning activities were carried out in two phases, Phase I in 2015 and Phase II in 2020, each involving specific tasks.

4.4.2. Decommissioning Practices

Decommissioning activities at Rubie and Renee can be categorized into two phases: Phase I and Phase II. Phase I primarily focused on the removal and recovery of subsea installations and pipelines. Notably, a Dive Support Vessel (DSV) and a Construction Support Vessel (CSV) were employed to prepare and recover these installations. Phase II was marked by a comprehensive approach, involving activities such as bathymetry site surveys, wellhead preparation for P&A campaigns for remaining wells, environmental site surveys, and over-trawl surveys.

4.4.3. Circular Economy Practices

The waste generated during both phases was effectively managed, emphasizing reuse and recycling. One notable example of CE-inspired reuse is the handling of concrete mattresses, where all 956 tonnes were sent to Augean North Sea Services for cleaning and subsequent reuse as sea defences in Peterhead and the Norfolk coast. This strategic reuse of concrete mattresses not only minimizes waste but also contributes to coastal protection, demonstrating a clear synergy between decommissioning objectives and broader CE benefits. Additionally, in the case of plinths, slabs, and other subsea structures, three plinths and three slabs, for a total of 64.2 tonnes, were sent for cleaning at Augean North Sea Services, facilitating their subsequent reuse. Similarly, 17 tonnes of the Cross-Over Structure (COS) are now being used by Fort William Underwater Centre for diver and ROV training. While the pipeline sections themselves were not suitable for direct reuse, their management followed the waste hierarchy approach. In effect, all pipeline sections were sent to shore for potential recycling. Recycling, while not the highest priority in the hierarchy, is still a sustainable option that conserves resources.

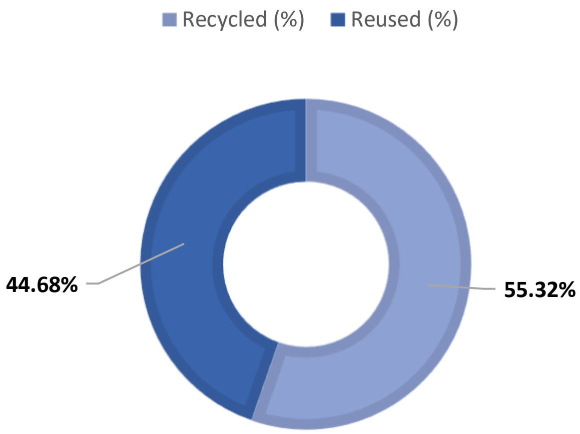

Figure 9: Renee and Rubie's Recycled and Reused rates of removed material.

4.5. Rose Field (SERL, 2018)

4.5.1. Project Overview

The Rose field decommissioning project, located in the Southern part of the North Sea, was initiated by SERL due to the unfeasibility of restarting gas production in the Rose well following issues with heavy liquid loading. The project involved decommissioning the Rose well and related infrastructure, including the Amethyst A2D platform, pipelines (PL1987 & PLU1988), Wellhead Protection Structure (WHPS), Xmas tree, and stabilization features such as concrete mattresses, grout bags, and deposited rock. SERL had previously achieved its first gas production in January 2004, with production ceasing in September 2010.

4.5.2. Decommissioning Practices

The decommissioning practices applied in the Rose field project encompassed a comprehensive approach to handling the various components of the infrastructure. The Rose well itself was abandoned. The removal of the WHPS, along with the clearance of the seabed aimed to leave the marine environment in its natural state, minimizing the potential ecological impact. Moreover, the approach to the 10" pipeline and umbilical sections involved flushing and leaving them buried in place, with only short-end sections removed to reduce future hazards. Additionally, the partial removal of umbilical sections within the J-tube at the Amethyst A2D platform reflects a strategic decision to extract materials that could be recycled while leaving others in place, considering both technical feasibility and environmental sustainability.

4.5.3. Circular Economy Practices

The Rose decommissioning project reported a significant percentage of materials being either recycled or reused. For instance, the WHPS, with a weight of 34.75 tons, was recycled, along with a 5.65-ton WHPS. Additionally, spools, pipeline sections, umbilical sections, concrete mattresses, and grout bags were efficiently recycled. However, only the tree, weighing 20 tons, was successfully reused. Therefore, even though has not been disclosed in the report, the final percentage of reusing has been around 3%.

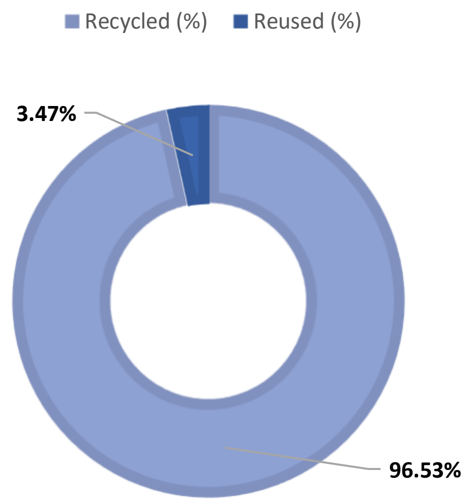

Figure 10: Rose's Recycled and Reused rates of removed material.

The table below shows a list of decommissioning methods and circular economy practices used in the selected case studies. In addition, per each field, the years of started and ceased production have been indicated.

Decommissioning Method	Circular Economy Practice
Leadon Field (2001-2004)	
- FPSO and Moorings Removal	- Reuse on another field
- Subsea Installations Removal	- Recycle
- Pipelines Partial Removal	- Recycle
- Mattresses Removal	- Recycle
Schiehallion And Loyal Fields (1998-2013)	
- FPSO Removal	- Reuse on another field
- Subsea Installations Removal	- Reuse on refurbished field
- Pipelines Partial Removal	- Reuse on refurbished field
Shelley Field (2009-2010)	
- FPSO Removal	- Reuse on another Field
- Subsea Installations Partial Removal	- Reuse on another field
- Pipelines Partial Removal	- Recycle
Rubie and Renee Fields (1999-2009)	
- Subsea Installations Removal	- Reuse of concrete mattresses for coastal protection; - Reuse of COS for diving; and - Reuse of plinths and slabs on another field
- Pipeline Partial Removal	- Recycle
Rose Field (2004-2010)	
- WHPS Removal	- Recycle
- Pipelines Partial Removal	- Recycle
- Subsea Installations Removal	- Reuse of tree onshore

5. Comparative Analysis

In this section, we delve into a cross-case analysis of the five decommissioning projects to identify patterns, trends, success factors, and challenges faced in integrating circular economy principles into offshore oil and gas decommissioning. The analysis provides valuable insights into the practical applications of CE practices in the decommissioning process.

5.1. Cross-Case Analysis

It is noteworthy that the format and content of the Closeout Reports examined in the previous chapter are largely consistent. Given the use of report templates, this might have been expected. In terms of developing CE and long-term sustainable waste management, it can be said that the analysis of the closeout reports that are currently available revealed that, regardless of iteration, their content is generic and their stated management strategies are frequently conventional. This reinforces the fact that decommissioning is "poorly understood" in the literature that already exists. As a result, it is not surprising that no reports mention CE. Positively, they frequently refer to the Waste Hierarchy (i.e., reduce, reuse, recycle, recover energy from waste, dispose of). However, there is a clear emphasis on the lower, more inferior reaches of the hierarchy. Although recycling and disposal are frequently mentioned, the reusing principle is noticeably, yet again, given very little attention.

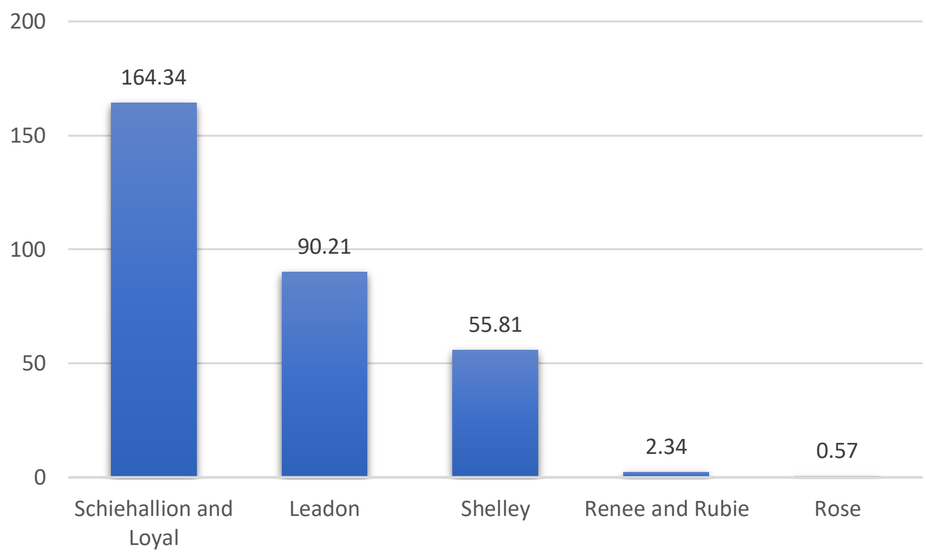

Figure 11: Dead-weight of selected fields (thousand tonnes)

Figure 11 shows the dead weight of the selected offshore fields, in thousands of tonnes. The dead weight of a field is the weight of all the infrastructure associated with the field, such as platforms, pipelines, and wells. The chart shows that the dead weight of the fields varies significantly, ranging from 57 tonnes for the Rose field to 164,340 tonnes for the Schiehallion and Loyal field. The average dead weight of the six fields is 90,478 tonnes.

The dead weight of a field is influenced by several factors, including the water depth of the drilling activity, which has a range from 24 meters of the Rose field to 550 meters of the Schiehallion and Loyal field, namely the lightest and the heaviest installations of the selected case studies.

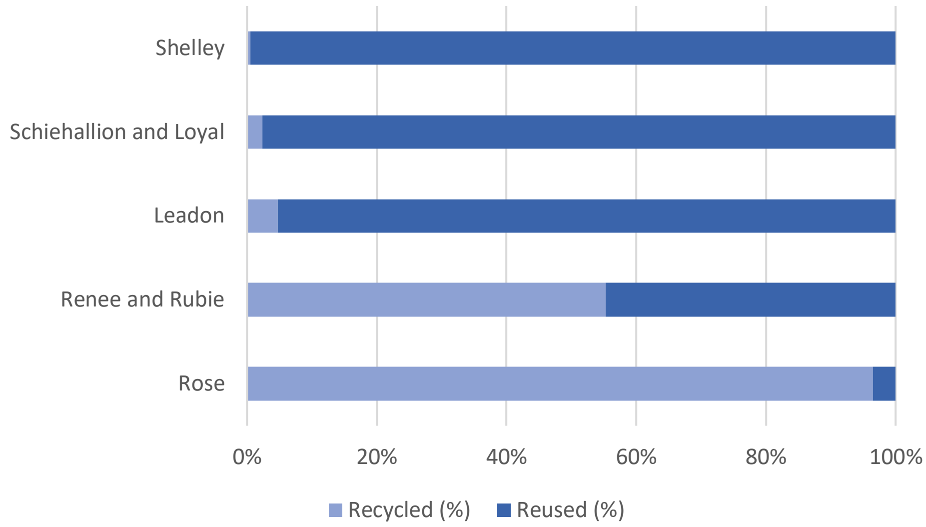

Figure 12: Recycled and Reused rates of removed material per case study.

Figure 12 shows the percentage of recycled, and reused items for the five offshore decommissioning case studies analysed. The percentage of recycled items ranges from 2.32% to 96.53% while the percentage of reused items ranges from 3.47% to 99.53%. The case studies with the highest percentage of recycled items are Rose (96.53%) and Renee and Rubie (55.32%). Meanwhile, the case studies with the highest percentage of reused items are Leadon (99.53%) and Schiehallion and Loyal (97.68%).

It is noteworthy that the field with the highest reuse rates also has the highest dead weight (Shelley). On the other hand, the case study with the highest recycling rates has the lowest dead weight (Rose). Specifically, there is a positive correlation of 0.77 between the reuse rates and the dead-weight tonnage, highlighting a strong correlation between reuse, and dead weight. This correlation is mainly related to the fact that the fields with the highest reused rates have relocated their FPSO to another field. In effect, the FPSO is the heaviest installation for the three floating fields with the highest reuse rates (Shelley, Schiehallion and Loyal and Leadon).

5.1.1. Identifying Patterns and Trends

There are observable patterns and trends in the case studies that have been investigated regarding the integration of circular economy principles. These trends include the following:

- **Recycling**: An important pattern that has been noted in all five case studies is a steadfast dedication to recycling. This dedication is demonstrated by the careful recycling of various materials, including but not restricted to steel, plastics, and electronics. The careful recycling efforts highlight the commitment to minimising waste and maximising the usefulness of materials, thereby reducing the ecological footprint of decommissioning activities. In all five case studies, there is evidence of a mixed approach when it comes to pipelines and flowlines. Some components are left in place, while others are recovered and recycled. One of the primary reasons for partial removal and recycling is technical feasibility. In some cases, it may be challenging or cost-prohibitive to remove all pipeline sections entirely. Therefore, only certain sections that are more accessible or easier to remove are taken out for recycling, while the rest are left in place.

- **Reusing**: Most of the cases that were investigated place a strong emphasis on the idea of reuse. The repeated practice of reusing Floating Production Storage and Offloading units to alternative offshore locations is particularly indicative of this emphasis. The Shelley Field stands out as one such instance, which distinguishes itself through its significant reuse of the FPSO, amounting to a staggering 55,000 tonnes, along with construction materials totalling 550 tonnes. Concerning all removed materials from the Shelley Field project, this outstanding achievement translates to an impressive reuse rate of 99.53%. Due to their reputation for adaptability and reusability, FPSOs become a pillar of CE practices in the context of offshore oil and gas production fields. The continued use of FPSOs in other fields or locations after decommissioning represents a crucial strategy for both increasing asset value and reducing waste generation because of the significant investment involved in them as well as their inherent capacity for transferability and redeployment.

5.1.2. Assessing Success Factors

Several important factors can be credited for the success of the aforementioned case studies in integrating circular economy principles and achieving decommissioning objectives, including:

- **Early planning**: The careful early-stage planning carried out for decommissioning activities was a fundamental component shared by all five case studies. This planning stage made it easier to find opportunities, evaluate risks, determine whether a project is feasible, and create detailed decommissioning plans. The careful selection of recycling and reuse techniques highlighted the thoroughness of the assessments made to determine the best decommissioning methods for specific components.
- **Collaboration**: Collaboration was found to be essential for successfully integrating the principles of the CE into the decommissioning process. This includes operators, service providers, and other stakeholders. The consideration of various viewpoints and the creation and implementation of the best solutions were both guaranteed by the collaborative synergy. It should be noted that some decommissioned parts, like concrete mattresses, found uses outside the oil and gas industry, demonstrating the potential for cross-industry cooperation in advancing CE practices.

- **Flexibility and Adaptability**: Projects that displayed more adaptability and flexibility in their decommissioning strategies showed improved effectiveness in incorporating CE practices. Strategic choices regarding the reuse, recycling, or preservation of components in their original locations were made possible thanks to this adaptability. For example, the Loyal Fields and Schiehallion projects encountered difficulties due to scope expansion, highlighting the need for flexibility and adaptability during decommissioning processes. Each project adapted CE principles to meet the needs and constraints of its unique context. The successful application of CE principles is based on this adaptability.

5.1.3. Challenges

The following challenges were faced in integrating circular economy principles into the case studies:

- **Cost**: Although adopting CE practices is inherently sustainable, there were some immediate cost challenges compared to using conventional decommissioning techniques. Notably, scope expansion led to additional costs when subsea installations were reused, as was the case in cases like Schiehallion and Loyal Fields. This phenomenon underlined the necessity of careful project planning and the proactive resolution of operational complexities during decommissioning to prevent the increase in costs. The cost analysis also showed that different financial outcomes were achieved for the decommissioning projects, including both cost savings and overruns. As a result, prudent cost control strategies became essential for achieving financial efficiencies.
- **Market Conditions**: The viability of markets for recycled materials and the corresponding demand for reused assets both had a noticeable impact on how practical CE practices were. The fluctuation in market conditions had a direct impact on the final project outcomes. Although not specifically stated in the available data, it is hypothetical that the market dynamics for reused materials may have influenced the choice between recycling and reuse in a few case studies. Additionally, the actual costs associated with the Rose Field initiative were significantly influenced by market rates for vessels and the resulting cost efficiencies. This circumstance highlights the significant influence of market dynamics on the factors affecting decommissioning expenditure.

6. Framework Development

In this section, we focus on the development of a comprehensive framework aimed at seamlessly integrating circular economy principles into the decommissioning processes of offshore oil and gas infrastructure. The framework is a culmination of the insights garnered from the cross-case analysis and interview of decommissioning projects and represents a practical guide for companies operating in the industry. The integration of CE principles into decommissioning involves a systematic approach that spans the entire lifecycle of offshore assets. This framework outlines five key steps to achieve this integration, of which each includes specific components.

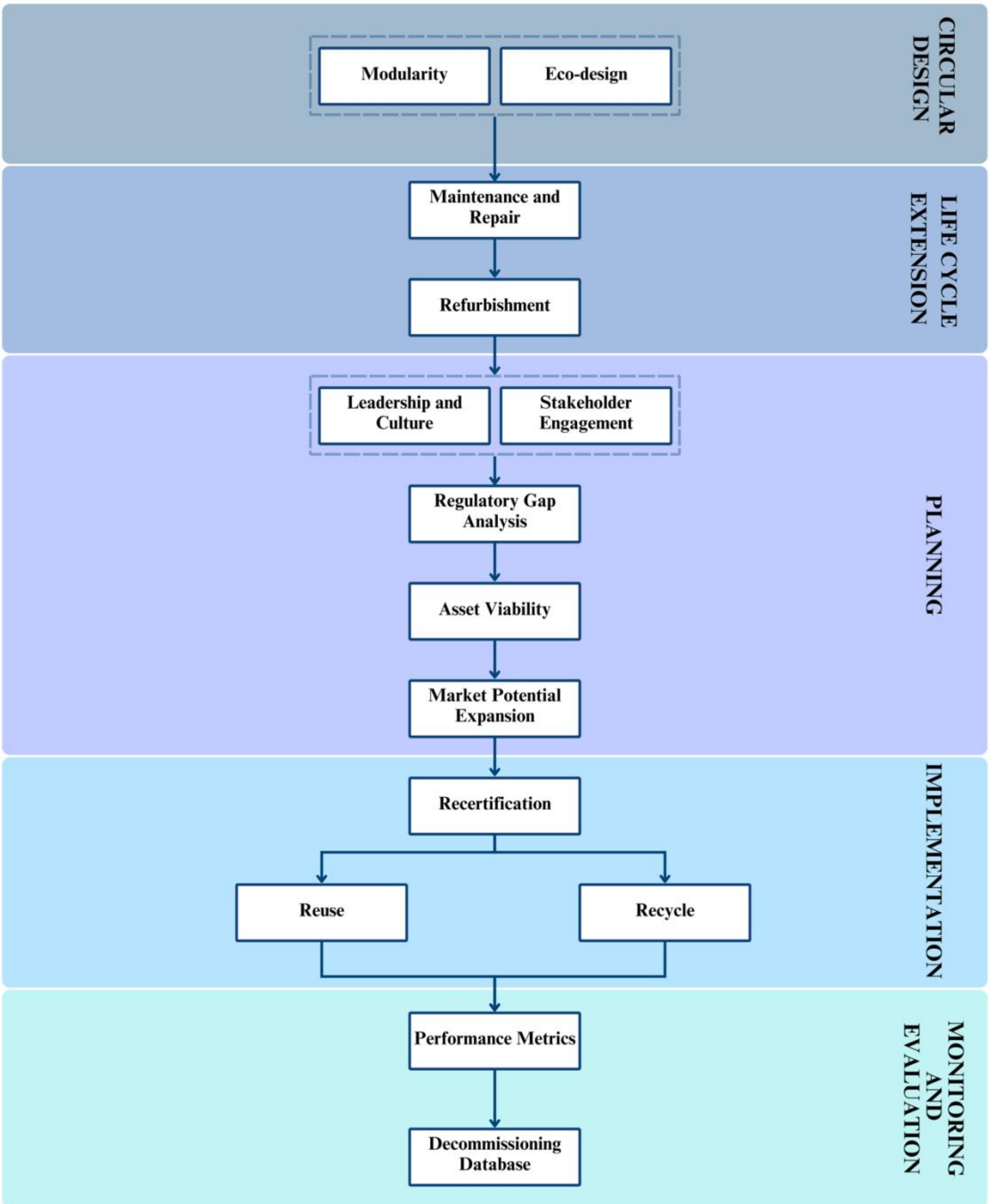

Figure 13: Circular Decommissioning Framework

6.1.1. Circular Design

While there is a growing push towards the adoption of renewable energy sources like offshore wind platforms as part of the broader energy transition movement, investments and activities in the oil and gas sector continue to involve the commissioning of new fields. Circular design serves as the fundamental principle of circular decommissioning. The necessity of including end-of-life considerations in the initial design of offshore platforms is emphasised in this stage. The main objective of circular design is to create durable assets that seamlessly integrate with circular economy practices. In this section, the value of modularity that enables simple disassembly and the recovery of valuable components during decommissioning has been discussed, together with eco-design principles, which emphasise shape optimisation and alternative materials to cut down on resource consumption and waste.

6.1.1.1. Modularity

When developing strategies for the adoption of circular economy practices in the decommissioning processes of the oil and gas sector, incorporating modularity is a crucial consideration. The incorporation of modular designs is essential for making asset disassembly relatively simple, thereby improving the chances of recovering valuable components during decommissioning activities. This strategy makes use of standardised parts, which not only makes it easier to categorise things systematically but also makes it easier to catalogue reusable modules. As a result, this method simplifies their upcoming deployment in projects. Modularity has also shown to be crucial in the field of high-value recycling. In contrast to conventional methods like the complete disintegration of components or structures through crushing and milling procedures, it serves as an efficient means of optimising the segregation and recovery of material streams with reduced contamination.

6.1.1.2. Eco-design

A key element in the realisation of a sustainable circular economy paradigm is eco-design. It includes the analysis and application of techniques for reducing resource consumption, including shape optimisation and the investigation of alternative materials. This circular design framework has the potential to reduce waste production and will be made possible by the wise use of sustainable materials and the lengthened lifespan of those materials.

6.1.2. Life cycle Extension

Oil and gas fields currently have an estimated designed life cycle of 25–30 years. A deliberate step towards circularity is the life-cycle extension phase. Maintenance and repair have been emphasised as having the potential to keep assets in their best condition before decommissioning planning is underway. Additionally, refurbishment demonstrates its ability to replace parts and modernise infrastructure while upholding circular principles. The Quad 204 project shown in the case study section demonstrates the practical application of circularity, highlighting the importance of modular design in refurbishment.

6.1.2.1. Maintenance and Repair

Extending the operational lifespan of facilities in the oil and gas industry requires maintenance, which is a crucial step in the process. To ensure the field's continued functionality, the focus of maintenance activities should be on performing routine inspections. This process may, if necessary, include repair procedures meant to return a component to its ideal operational state. Insights from interviews, in particular, highlight the importance given to maintenance and repair activities throughout the field's lifecycle, but it has been noted that as decommissioning plans are developed, these crucial activities frequently receive less attention. Companies in this industry must reevaluate how they operate, considering the advantages of asset preservation from an economic and environmental perspective to ensure that assets are in the best possible condition for decommissioning.

6.1.2.2. Refurbishment

By replacing some of the components with newer, better-performing ones, refurbishment can extend the service life of offshore fields. While many parts are replaced or repaired, the overall structure of a field maintains its overall integrity, leading to an overall "upgrade" of the entire infrastructure. According to Schiehallion and Loyal's Quad 204 project, which was demonstrated in the case study section, their objective of extending the life of the fields beyond 2035 could be reached through the replacement of the current FPSO vessel with a larger one. The CE principles are truly integrated into the refurbishment of offshore platforms, where depending on the refurbishment strategy, it may use repaired or reused components. Additionally, replaced parts can be used in other industries for reusing or added to the recycling stream. In the Quad 204 project, the prior FPSO was sold to a different field. Moreover, the use of common modules over specialised ones for repair or replacement is made possible by modular design, which also helps to prevent the irreversible joining of various materials and components, especially when their predicted lifetimes differ.

6.1.3. Planning

In the context of an O&G company's integrated framework, the development of a tailored circular decommissioning strategic plan is crucial. Planning establishes the road map for successful circular decommissioning, identifying its milestones to be able to assess the successful CE integration. The first step in overcoming cultural barriers in the oil and gas industry is developing leadership and a culture of circularity. Assessing an asset's viability entails early reusability evaluation and streamlining circular initiatives. Compliance is improved through regulatory gap analysis, which ensures alignment with evolving circular economy regulations and guidelines. Stakeholder engagement develops working relationships and identifies important players in the circular ecosystem. Finally, the CE practices' emphasis on cross-sectoral synergy is highlighted by expanding into potential markets within strategic sectors.

6.1.3.1. Leadership and Culture

The literature review made clear that cultural foundations are the main barrier to the incorporation of circular economy principles into decommissioning practices in the oil and gas sector. Insights from interviews also highlight the O&G sector's historically conservative mindset in contrast with recent efforts to strengthen its adherence to sustainable methodologies. It is crucial to acknowledge the significant obstacles, including those based on culture, that prevent component reuse initiatives from being widely adopted. These obstacles can be overcome by consciously adopting a long-term strategy that supports such initiatives and is characterised by the setting of clear objectives and expectations regarding circularity. It is crucial to ensure organisational alignment with these goals. Starting a cultural transformation requires recalibrating cultural norms, competencies, project guidelines, technical requirements, and contractual agreements. At the same time, supply chain management practices must be optimized to make CE more pervasive. It is essential to raise awareness among institutional and corporate stakeholders for the effective integration of CE principles. Facilitating cross-sectoral knowledge exchange appears to be an extremely beneficial strategy in addition to encouraging engagement solely with O&G organisations and associations. The O&G industry and businesses at the forefront of reuse practices may need to organise forums and workshops to promote communication and knowledge transfer. The focus of this cultural shift should also be on offshore platform designers, a stakeholder that frequently has little understanding of the decommissioning processes that take place at the end of an asset's lifecycle and little awareness of how their design choices may affect recovery rates and procedures.

6.1.3.2. Asset Viability

Before beginning any decommissioning efforts in the oil and gas industry, a thorough assessment of the viability of reusing existing materials and components is an essential requirement. This assessment process may start earlier on in the platform's operational lifespan, even while it is still in place, and potentially before production activities stop. It necessitates a thorough examination that considers the evaluation of asset condition, historical operational performance, and the investigation of alternative opportunities for re-utilisation. This evaluation process assumes the role of a discriminating criterion governing the fate of each component of the field and maximises the possibility of reintegration of materials and components into the industrial ecosystem. In-depth connections between the decommissioning project's latent opportunities and the circular economy's guiding principles are revealed by this meticulous analysis.

6.1.3.3. Regulatory Gap Analysis

The decommissioning and CE regulations framework is evolving, as was noted in the literature review. Determining the conditions for compliance and advancing environmental standards necessitates a thorough examination of the current regulatory framework, including the most recent guidelines. To ensure seamless compliance with legal and environmental mandates, a thorough investigation aims to pinpoint areas where CE practices can be harmonised with current regulations and guidelines. For instance, the EU Circular Economy Action Plan outlines several initiatives to support material reuse, repair, and recycling. These actions include establishing goals for recycling and waste reduction as well as offering financial incentives to companies that implement circular business practices. The key findings from the interview highlight the importance of certification bodies in outlining regulations and specifications for decommissioning, stressing the necessity of observing legal requirements and highlighting the crucial role they play in outlining and promoting industry best practices.

6.1.3.4. Stakeholder Engagement

Fostering cooperative relationships with key stakeholders, such as public and private organisations, decommissioning project implementers, regulators, and other parties involved in or affected by the project, is essential. Stakeholder participation early on in the project enables proactive anticipation of obstacles and expectations. An environment in which CE practices can be applied is created by the development of strategic alliances with significant O&G industry players as well as service providers from other industries. To meet CE objectives, companies must learn to recognise, interact with, and listen to stakeholders. To identify relevant stakeholders and analyse their potential impact on the circular decommissioning project, a stakeholder assessment is crucial. Finding the best-fit suppliers who can help achieve CE objectives while minimising the negative effects of their activities requires careful consideration of the entire supply chain in this process. To obtain useful opportunities and information that can support the decision-making process and, as a result, the integration of CE practices, the most pertinent stakeholders based on their influence should be actively engaged.

6.1.3.5. Market Potential Expansion

Investigating potential markets is crucial, and this should be accompanied by a careful examination of the kinds and quantities of materials that are readily available. Finding synergistic opportunities within well-established industries is a crucial part of achieving CE goals. To foster collaborative relationships and realise the circular economy paradigm's full potential, it is crucial to actively engage and stimulate potential target markets, such as construction ones given the high rates of steel components in offshore fields.

6.1.4. Implementation

During the implementation, the focus is on concerns about material reliability which are addressed through recertification, giving end-users of reused parts more assurance. In alternative, recycling the components that cannot be reused is still a significant CE activity which avoids taking waste to landfill.

6.1.4.1. Recertification

Reliability of materials and components was brought up in the discussion with the oil and gas expert as well as in the literature, where it is one of the major issues with the reuse principle. Regardless of its relative cost advantages or benefits from reuse, some buyers may be reluctant to buy an item if its future performance is uncertain. Recertification has been incorporated into this framework because it could potentially support CE principles. Giving quality guarantees about the procedures used as well as the quality of materials and components is crucial to removing barriers to the adoption of circular economy practices.

6.1.4.1. Reuse

The adoption of the reuse principle holds significant value, going below only the reduction principle, from both a financial and environmental standpoint, as shown by the body of literature currently in existence. This value results from the ability to recertify and reuse components and materials, not only within the same industry but also across various contexts. Typically designed for specific uses, the majority of machinery used in the oil and gas industry rarely retires outside of the energy industry. On the other hand, opportunities for reuse in markets and industries different from their original intended purpose become viable propositions for smaller components, including both electrical and mechanical components.

6.1.4.2. Recycle

Components that cannot be successfully reused are then put through the recycling process. The recovery of materials requires a separation procedure based on the fundamental material composition, and subsequently their reintroduction into the recycling market. With a focus on the modular approach, this crucial separation process is systematically aided from the start of the circular design.

6.1.5. Monitoring and Evaluation

Beyond materials input/output ratios, performance metrics also consider social impact and cost reduction. The creation of a decommissioning database becomes an essential tool for industry collaboration and data-driven decision-making. This stage guarantees that the integration of the circular economy remains transparent, quantifiable, and flexible.

6.1.5.1. *Performance Metrics*

It is essential to develop a set of precisely defined key performance indicators (KPIs) to establish a comprehensive framework for assessing the effectiveness of circular economy integration within the decommissioning processes of the oil and gas sector. These KPIs should not only include the typical metrics for material inputs and outputs but, inter alia, additional metrics to support the integration of CE practices into decommissioning operations.

Following the conceptualisation of "Circular Society" (Calisto Friant et al., 2020), it is critical to acknowledge that CE practices may produce a range of societal advantages. This is a factor that is especially relevant in the context of decommissioning, where the workforce is "decommissioned" concurrently with the field assets. In this situation, it is crucial to promote job creation to mitigate the negative effects of job displacement. As a result, a KPI that measures social impact and societal sustainability during decommissioning is the ratio between jobs created and lost.

Additionally, the evaluation of the shift to circular decommissioning should go beyond just listing the costs related to the technical aspects of decommissioning activities. Practitioners must demonstrate the cost savings brought about by the reuse and/or recycling of materials and assets. This practice not only demonstrates how CE principles can be applied but also supports the potential financial gains associated with using a circular decommissioning strategy. Therefore, a best practice for demonstrating the financial benefits associated with circular decommissioning practices is, inter alia, to include a KPI that quantifies the cost savings derived from material and asset reutilization.

6.1.5.2. *Decommissioning Database*

A significant inflow of data is required for circular economy (CE) initiatives in the context of offshore oil and gas decommissioning. This demonstrates how important it is to set up reliable data systems and cooperative mechanisms for disseminating information about resource stocks and flows within the O&G industry. These data systems are essential for clarifying the scope of opportunities and challenges, both in terms of the quantity and quality of components and materials. This repository of knowledge about quantity, technical characteristics, and the corresponding environmental, social, and economic values plays a crucial role in promoting the shift to a more CE. In their efforts to adopt CE practices within decommissioning activities, governmental entities and corporate enterprises should make decisions based on this body of knowledge.

Numerous benefits could arise from the creation of an extensive international repository for offshore decommissioning activities. The facilitation of contractor investments, which reduces barriers in the supply-demand dynamic, is the primary benefit of this. Additionally, the creation of such a repository simplifies the benchmarking and assessment of decommissioning costs, improving budgetary accuracy and performance evaluation. This repository acts as a catalyst for locating opportunities for cooperation between operators and suppliers by outlining the temporal and asset-specific characteristics inherent to decommissioning projects. In the end, it is crucial to highlight and promote stakeholder cooperation and material reuse, which in turn helps the reuse market expand.

6.1.6. Circular Decommissioning Framework's Contribution to SDGs

The Circular Decommissioning Framework presented here encompasses five essential phases: Circular Design, Life Cycle Extension, Planning, Implementation, and Monitoring and Evaluation. Each phase of this framework aligns with specific SDGs, offering opportunities for the oil and gas industry to contribute to a sustainable future. Table 4provides an overview of how each phase of the proposed framework aligns with specific Sustainable Development Goals (SDGs). It highlights the contributions of the framework to sustainable infrastructure, responsible production, resource efficiency, and various other dimensions of sustainable development.

Table 4: Circular Decommissioning Framework's Contribution to SDGs

Framework Phase	SDG No.	Contribution
Circular Design	SDG 9	This phase promotes sustainable infrastructure and responsible production by focusing on modularity, eco-design, and resource efficiency. It involves incorporating end-of-life considerations into the initial design of offshore platforms. The aim is to create durable assets that seamlessly integrate with circular economy practices. This phase emphasizes modularity, which enables easy disassembly and the recovery of valuable components during decommissioning. It also promotes eco-design principles, such as shape optimization and the use of alternative materials, to reduce resource consumption and waste.
	SDG 12	
Life-cycle Extension	SDG 9	Extending the life cycle of oil and gas fields aligns with sustainable infrastructure and responsible production, reducing the need for new resource extraction. It emphasizes maintenance, repair, and refurbishment to keep assets in good condition before decommissioning. Refurbishment includes replacing components with newer ones while maintaining the overall integrity of the infrastructure. Modular design plays a crucial role in refurbishment, allowing for efficient component replacement.
	SDG 12	
Planning	SDG 12	Planning contributes to responsible consumption and production by optimizing resource use and compliance with circular economy regulations. Additionally, it involves stakeholder engagement, which aligns with partnership-building. It involves developing a strategic plan tailored to the oil and gas company's needs. This phase includes leadership and culture development to overcome cultural barriers, assessing asset viability for reusability, regulatory gap analysis to comply with circular economy regulations, stakeholder engagement, and exploring potential markets for materials.
	SDG 17	
Implementation	SDG 9	Implementation focuses on material reliability through recertification, reusing components, and recycling. This reduces waste and promotes responsible production and innovation. It includes recertification to provide end-users with assurance regarding reused parts. It also involves reusing components when possible and recycling those that cannot be reused, aligning with circular economy principles.
	SDG 12	
Monitoring and Evaluation	SDG 8	Monitoring and evaluation include assessing social impact and demonstrating cost savings through circular practices. It includes performance metrics that assess not only material inputs and outputs but also social impact and cost reduction. Establishing a decommissioning database is crucial for data-driven decision-making and industry collaboration. This contributes to decent work, economic growth, and responsible consumption and production.
	SDG 12	

7. Discussion and Conclusion

In this study, a comparative case studies analysis to explore the integration of circular economy (CE) principles, particularly recycling and reusing, in offshore oil and gas decommissioning processes has been.

Concerning *RQ1*, the comparative analysis of five offshore O&G decommissioning projects offers valuable insights into the successful integration of CE principles, particularly recycling and reusing, into the complex processes of dismantling and retiring offshore infrastructure. As also emerged in the interview, a prominent finding across all cases is the commitment to recycling, underscoring a shared dedication to waste reduction and the optimization of material resources. Equally significant is the pronounced emphasis on reusing assets, exemplified by the extensive reuse of Floating Production Storage and Offloading units, such as in the Shelley Field project, which achieved a reuse rate of 99.53%. This practice not only exemplifies adaptability but also underscores the economic and environmental advantages of reusing offshore assets. Key success factors identified in our analysis include meticulous early-stage planning, fostering collaboration among industry stakeholders, and maintaining flexibility throughout decommissioning strategies. However, it's important to acknowledge the challenges that emerged during this integration process. Notably, there were cost implications associated with CE practices, particularly in cases involving the reuse of subsea installations, as seen in the Schiehallion and Loyal Fields project. This financial hurdle underscores the importance of prudent cost management and planning to ensure that CE objectives do not lead to unforeseen financial overruns. Market conditions for recycled materials and particularly for reused assets also played a substantial role in determining the practicality of CE principles. The dynamic nature of these markets directly influenced the outcomes of certain projects, particularly the Rose Field initiative, where market rates for vessels significantly impacted costs.

In response to *RQ2*, a comprehensive framework aimed at facilitating the seamless integration of CE principles into offshore O&G decommissioning processes has been developed. This framework encompasses five distinct phases: circular design, life cycle extension, planning, implementation, and monitoring and evaluation. Each phase is designed to address specific challenges and capitalize on identified success factors. **Circular Design** is the foundational phase, emphasizing the need to consider end-of-life aspects during initial platform design. Modularity is highlighted as a critical element, enabling easy disassembly and component recovery during decommissioning. Eco-design principles, such as shape optimization and alternative materials, are also emphasized to reduce waste and prolong material lifespan. **Life Cycle Extension** focuses on extending the operational life of offshore assets. Maintenance and repair are key aspects, ensuring assets remain in optimal condition before decommissioning planning begins. Refurbishment, illustrated by the Quad 204 project, showcases circularity by replacing parts and modernizing infrastructure, with modular design playing a pivotal role. **Planning** is a pivotal phase, setting the roadmap for successful circular decommissioning. Findings stress the need for a culture shift towards circularity, early assessment of asset reusability, alignment with evolving circular regulations, stakeholder engagement, and exploring markets for material reuse. **Implementation** focuses on material reliability through recertification, reuse of components, and recycling of materials that cannot be reused. **Monitoring and Evaluation** ensure the effectiveness of CE integration. Performance metrics go beyond material metrics to include social impact and cost reduction. The creation of a decommissioning database aids data-driven decision-making, cooperation, benchmarking, and stakeholder collaboration, expanding the reuse market.

The Circular Decommissioning Framework is a strategic approach for the oil and gas industry to align its operations with the Sustainable Development Goals (SDGs) considering the global imperative for sustainable development. This framework offers a multifaceted approach that significantly and directly advances multiple SDGs. It supports SDG 8 (Decent Work and Economic Growth) by emphasizing the assessment of social impact, particularly job creation, which is crucial for several countries, given the fact that offshore platforms are strategically positioned on the continental shelves of 53 countries (Parente et al., 2006). SDG 9 (Industry, Innovation, and Infrastructure) is contributed using circular design and life cycle extension to promote resilient and innovative industry practices, which lessens the need for new resource extraction. The implementation phase supports industry innovation, further supporting this objective. Concerning the SDG 12 (Responsible Consumption and Production) life cycle extension phase increases the operational lifespan of assets, thereby extending their useful lives and lowering disposal and the consumption of new resources, circular design concentrates on minimising resource use and consequently waste generation. The circular economy regulations are adhered to through planning, and material reliability is prioritised through recertification during implementation. Monitoring and evaluation demonstrate cost savings and environmental advantages of recycling and reusing materials, quantifying the advantages of responsible consumption and production practices. Lastly, SDG 17 (Partnerships for the Goals) is emphasized in the planning phase which actively encourages partnership building and stakeholder engagement. The framework supports partnerships to achieve shared circular economy goals by encouraging collaboration among a range of stakeholders, including public and private organisations, regulators, and industry players. This is in line with SDG 17's spirit.

7.1. Implications for Theory and Practice

This research contributes to the growing body of research on circular economy principles in the context of decommissioning expanding the understanding of how CE has been integrated as well as offering practical insights for businesses seeking to adopt CE principles within decommissioning projects. The developed framework offers practical guidance for companies involved in decommissioning projects, providing a systematic approach to integrate CE principles.

7.1.Research Limitations and Future Research Directions

While this study offers valuable insights, it is essential to acknowledge its limitations. The analysis relied on available data from completed decommissioning projects, limiting the investigation of ongoing initiatives. Additionally, the findings are based on a limited number of projects limited to the UK Continental Shelf. In addition, it is imperative to acknowledge that this framework does not present a solution feasible for addressing all the multifaceted challenges and opportunities inherent in this sector. Expanding the comparative analysis to include decommissioning projects from various regions can provide a broader perspective on circularity practices and conducting longitudinal studies to track the long-term impact of circular economy integration in decommissioning projects can reveal evolving best practices and challenges.

Appendices

Case Study Reports

Britoil Limited. (2018). *Schiehallion and Loyal Phase 1 Decommissioning Close Out Report*.

Hess. (2021). *Rubie and Renee Decommissioning Close Out Report*.

Premier Oil. (2012). *Shelley Field Decommissioning Programmes Close Out Report*.

Spirit Energy. (2018). *Rose Decommissioning Close Out Report*.

Total Energies. (2022). *Leadon Field Decommissioning Programme Close Out Report*.

Interview Transcript

Q: The oil and gas industry is often described as resistant to change. Can you explain how this resistance to change influences offshore platforms?

R: The oil and gas industry has traditionally been conservative and inclined to prefer proven installations over experimenting with new technical solutions. This attitude has been partly due to the need to operate and maintain, in unconventional conditions, extremely reliable plants capable of guaranteeing both maximum operational efficiency and very high standards in terms of the safety of people, the environment and the assets themselves. Technological innovation is undoubtedly a strategic factor for change, but it is equally correlated with a risk of failure, which must necessarily be identified and mitigated, and lower reliability at the start of the cycle, all the more so if the innovation is brought to plants, systems and structures that operate in extreme and remote conditions such as offshore platforms. However, over the past decade, there has been an increasing focus on sustainability, materials used, installation of new emission monitoring systems, refurbishment of existing facilities with new and more efficient plant and machinery, spill prevention, and the ongoing search for new, green and clean technologies, and innovative hybrid systems. In the past, less attention was paid to environmental impact, often focusing on the soundness and integrity of assets and operations. Today, however, pressure and attention from various stakeholders, including governments in more advanced economies, has led to improved materials, a shift in their use, and the adoption of more sustainable practices. In addition, a further change has been the role of fixed platforms, which has also shifted to the wind sector through their use for the installation of electrical substations connected to offshore installed wind turbines rather than just conventional drilling and hydrocarbon extraction.

About the oil & gas sector, fixed platforms are less and less used because hydrocarbon exploration and related drilling and extraction activities have increasingly shifted to deeper sea depths. In this context, fixed platforms have been replaced by mobile rigs.

Q: How do you evaluate the regulatory framework that governs offshore platform decommissioning?

R: Decommissioning is to all intents and purposes a phase in the life cycle of platforms. Just as offshore construction and installation are regulated, so is decommissioning regulated by international (IMO: International Maritime Organisation), national and local marine conventions and by the guidelines and recommended practices of certification bodies. Certification bodies such as DNV, RINA, ABS, Bureau Veritas, global leaders offering testing, inspection and certification (TIC) services, play a key role in defining the rules, requirements and recommended practices for marine decommissioning operations and verifying their compliance with the regulatory framework. They also provide risk analysis services, safety and environmental audits, supervision, technical and operational feasibility, during the decommissioning phase.

Q: How do companies manage the lifecycle of offshore platforms, and what are their strategies as they approach the end of a platform's lifecycle?

R: Companies manage the life cycle of offshore platforms with a focus on maintenance. The latter takes place in ordinary activities during the operational life and extraordinary activities performed during the so-called downtime windows. Usually, extraordinary maintenance activities coincide with activities to improve and renovate existing installations by making them more innovative and efficient. In the latter case, both the objective of renewing the installed systems and extending their life cycle are pursued. On average, the life cycle of these plants is about 25-30 years. Afterwards, about 5 years before the expected end of the cycle, further investments in improvements or renovations are often avoided, as decommissioning activities are already planned. The motivation is purely economic, since considering that in the short to medium term the asset will be decommissioned and will no longer produce monetary income, an attempt is made to minimise operating costs to increase margins.

Q: What is the main approach to circular economy principles in offshore platform decommissioning?

R: In the decommissioning of offshore platforms, the main and most realistic objective is recycling. Indeed, unfortunately, the reuse of materials and machinery is often limited due to the advanced age of the structures.

In terms of lower environmental impact and consumption/emission reduction, the AllSeas company is a remarkable example in the industry. It is completely designed in-house, the world's largest construction vessel capable of installing and especially removing fixed offshore platforms. Undoubtedly, it has represented a significant change in offshore decommissioning with considerable impact in terms of sustainability. The 'Pioneering Spirit' is single-handedly capable of lifting both platforms and jackets in a single lift, drastically reducing the amount of associated offshore activity and associated displacement of several vessels. Despite a high initial investment of around 2 billion, the company's strategic decision to invest in the design and construction of a vessel that currently represents a 'unicum' in the sector will surely have been supported by *sound forecasts that will see the importance of decommissioning, and especially its environmental impact, grow in the future.*

Q: Considering the growing interest in offshore wind energy, are there potential synergies between offshore platform decommissioning and the circular economy in this sector?

R: At present, there seem to be limited opportunities for synergy between the decommissioning of oil platforms and offshore wind power. O&G platforms are often located offshore, while offshore wind farms are usually located closer to land for reasons also related to energy conversion and efficiency. However, rather than attempting to reuse existing platforms at the end of their lifecycle, the wind energy industry is developing new technologies for fixed foundations (e.g., Gravity Base) and floating wind-oriented solutions. Therefore, the re-use of oil platforms for the construction of offshore wind power plants is currently hardly practised and feasible.

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