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ARTICLE

Multi-Attribute Considerations for the Conversion of Offshore Oil and Gas Platforms into Offshore Wind Turbines

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ABSTRACT

Many offshore oil and gas platforms worldwide will need to be decommissioned in the foreseeable future due to reserve depletion, entailing significant costs for petroleum operators. Reusing offshore oil and gas platforms, particularly the jacket support structures, for offshore wind turbines can be an alternative to complete platform removal. While this option can reduce decommissioning costs, there are technical, economic, environmental and legal issues to be considered. This paper aims to scrutinize such issues and develop a decision-making framework for the conversion of offshore oil platforms into offshore wind turbines. This is achieved through the review of relevant technical guidance, laws and literature, and a case study, studying two offshore oil platforms, X and Y, in Vietnam's continental shelf. The main technical aspects requiring attention include corrosion protection for the structures, the site conditions and loads acting on the structures, and the fatigue design. From an economic perspective, the conversion could eliminate the costs of jacket removal and reduce by half the costs of platform preparation, mobilization of derrick barges, and project management. Following this, repurposing platform Y could save about one-seventh of the total decommissioning cost. From the environmental viewpoint, the steel structures of offshore oil jackets could enhance biodiversity. The conversion is acceptable under the current legal international and national frameworks of the UK, Australia and Vietnam for offshore decommissioning; therefore,

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converting platforms X and Y into offshore wind turbines is legally feasible, subject to demonstrating benefits and satisfying safety requirements under Vietnam's laws.

Keywords: Offshore Oil and Gas; Offshore Wind Turbine; Decommissioning; Repurpose; Retrofit; Rig-to-Reef

1. Introduction

Globally, about 2,800 offshore petroleum installations will be decommissioned in the upcoming decades as reserves become depleted [1]. Operators are legally obliged to decommission the structures at the end of the production life, and the costs of complete removal are high, estimated between 28 and 39 billion euros for the North Sea only [2]. Decommissioning costs for each shallow-water rig in the Gulf of Mexico can be between $500,000 and $4 million, with the rigs varying from single-pile, one-well platforms, located in several feet of water, to larger, four-pile structures in water depths up to 120 m [3]. While financial assurance instruments have been set up worldwide, there are still uncertainties associated with such bonding mechanisms to secure the operator's liability for decommissioning [4,5]. In such a context, alternatives to complete removal that can save decommissioning costs can provide incentives for operators, apart from helping them to fulfill legal obligations.

Many governments have recently prioritized offshore wind to achieve the net-zero carbon emission target. The United Kingdom (UK), the world leader in offshore wind, contributing about 20% of global offshore wind capacity with 11.3 GW operational, has planned to reach a total offshore wind capacity of 43–50 GW by 2030 [6,7]. Vietnam, while currently having no operational offshore wind projects, aims for about 21,000–32,032 MW and 353,503–379,097 MW in terms of total offshore wind electricity production capacity by 2035 and 2050, respectively [8,9]. Given the similarities between the petroleum and wind industries, converting a fixed offshore oil platform into an offshore wind turbine can be an alternative decommissioning strategy.

In practice, few projects have been undertaken; the only known example to date is the retrofitting of an abandoned jacket structure named SZ36-1, located in the Liaodong Bay at a depth of 31 m, with ice and earthquake being the control environmental loads, into an offshore wind turbine by China National Offshore Oil Corporation in 2007 [10]. Furthermore, while some studies have been implemented to explore the feasibility of converting offshore oil and gas platforms into offshore wind turbines, to the best of the authors' knowledge, no focus was put on identifying the critical issues that influence such conversion, which help inform the decision-making process of offshore oil and gas decommissioning. Therefore, this paper aims to investigate such issues, which are the technical, economic, environmental and legal factors, based on which a decision-making framework is developed and relevant recommendations are provided. These objectives will be achieved through the synthesis and comparative analysis of the relevant technical guidelines, academic papers, as well as the international and national legal frameworks of the UK, Australia and Vietnam for offshore oil platform decommissioning. The study was started by the review of the literature on the conversion of offshore oil and gas platforms into offshore wind turbines, based on which the technical and economic factors were found to be important and most explored. As the authors aim to address the research question from the management perspective, environmental and legal aspects were also considered apart from such technical and economic factors. This research underwent the appraisal of an evaluation committee, which suggested the key technical issues to be investigated, including the corrosion and fatigue of the aged offshore oil platforms, which were thus the research focus. While investigating these issues, the authors found the guidelines and standards set up by the Det Norske Veritas (DNV), American Petroleum Institute (API) and International Electrotechnical Commission (IEC) provide comprehensive guidance for petroleum operators and wind developers in designing offshore oil platforms and offshore wind turbines; however, they have not been much analyzed in academic papers. Therefore, they were synthesized and compared to provide a comprehensive insight into the key technical issues. For the economic factor, the authors were particularly interested in how the conversion could save decommissioning costs, and balance the costs and benefits compared to a newly constructed wind turbine. Regarding the environmental aspect, as rig-to-reef (RTR) is a preferred decommissioning option in many parts of the world, the authors were intrigued by the combination of RTR (for the substructure of the offshore oil platform) with repurposing the topside of the platform for a wind turbine. From a legal standpoint, the conversion involves leaving the offshore oil platform in situ, which needs to be accepted under the international and national legal frameworks for offshore oil decommissioning. In this regard, the legal frameworks of the UK, Australia and Vietnam were scrutinized, since the UK is seen as having extensive experience in offshore oil decommissioning, while the decommissioning industry is still in its infancy in the latter two countries. In addition, a case study of two offshore oil platforms in Vietnam was conducted to demonstrate the feasibility of reusing offshore oil platforms for offshore wind turbines. However, no thorough analysis of all the technical, economic and environmental aspects could be conducted for each platform, due to the limited data availability.

This paper is organized as follows: Section 2 presents a literature review on repurposing offshore oil and gas platforms for offshore wind power generation. Then, a background regarding offshore oil and gas decommissioning, design categories of offshore oil platforms and offshore wind turbine substructures, offshore wind turbine components, and offshore wind farm assets is delivered in Section 3. The analysis of the technical, economic, environmental and legal aspects associated with the conversion of offshore oil and gas platforms into offshore wind turbines is elaborated in Section 4. The case study and the discussion are laid out in Section 5 and Section 6 respectively, followed by the conclusions and outlook.

2. Literature Review

Research on the conversion of offshore oil and gas platforms for offshore wind power generation mainly focuses on the evaluation of the technical and economic feasibility of this option compared to the total removal of the platforms as the traditional decommissioning approach. Bingol [11] evaluated the feasibility of reusing an offshore oil and gas platform, with over 20 years of operational life, near Istanbul, Turkey, for retrofitting with a wind turbine. For more realistic results, the evaluation was based on the combination of recent offshore economic models with up-to-date scientific wind energy yield assessment models. Baqery and Edalat [12] recommended a knowledge-based system for the selection of decommissioning options for fixed offshore jacket platforms in the Persian Gulf. The authors considered the economic costs and benefits of two options: (i) complete removal and (ii) repurposing the abandoned jacket structure of a platform in the Persian Gulf into an offshore wind turbine, comparing the total decommissioning cost of the former and the Net Present Value of the latter. Both Braga et al. [13] and Barros et al. [3] evaluated the technical and financial viability of converting oil and gas platforms offshore Brazil into wind turbines. However, Braga et al. [13] paid attention to the Capital Expenditures (CAPEX) of such conversion, which can be offset by the decommissioning costs, in comparison with installing fully new offshore wind turbines, whilst Barros et al. [3] differentiated the Levelized Cost of Electricity (LCOE) of the retrofitted Brazilian offshore wind farms from those of the US offshore wind farms.

One of the technical issues that needs to be taken into account when reusing an offshore oil platform for an offshore wind turbine is the fatigue life of the aged oil platform, which has gained interest from scholars recently. Liu et al. [14] presented a fatigue reliability-based evaluation framework, focusing on the structural performance of the converted offshore oil platform under extreme sea states. Different from offshore oil platforms, offshore wind turbines are categorised as low-consequence unmanned platforms and exposed to dramatic overturning moments induced by wind loads on the turbine. Given the differences in the operational conditions and the related risks, a common approach for decreasing the mass is optimizing the size. For instance, Liu et al. [14] increased the leg thickness of the reference jacket and decreased its brace diameter by

20%. While both the converted offshore platform and the optimized offshore platform for offshore wind turbines can withstand the potential loads under extreme sea states, further retrofitting may be required for the former, particularly increasing the leg thickness [14]. In the earlier work, these authors also presented a fatigue reliability-based framework, but such a framework integrates metocean data analysis, structural analysis, life cycle evaluation, and revenue optimization to evaluate the expected life cycle of a repurposed platform [15]. Similar to Heo et al. [15], Dinh and Vu [16] introduced an approach for estimating the fatigue life of the jack-up leg structure of offshore oil and gas platforms, which was based on Palmgren-Miner's rule. Nevertheless, these authors suggested a new formula for determining the total fatigue damage with alternative fraction factors to replace the approximate method which presumes the fatigue life is equivalent to 80% of design life and disregards fatigue damage in transit conditions [16].

Some scholars have made efforts to develop models of offshore wind turbines retrofitted on offshore oil and gas jackets. Particularly, Wang et al. [10] developed and analyzed a model for reusing an offshore oil and gas jacket as the structure base for an offshore wind turbine in the heavy ice conditions of Bohai Gulf, China, utilizing the ABAQUS finite element analysis software. The model enabled the ultimate strength analysis, earthquake analysis, fatigue assessment and buckling strength calculation of the retrofitted wind turbine, following which the turbine structure would meet the relevant requirements for the next 20 years of service life [10]. Since such a model deals with important technical issues to be considered for a repurposed jacket, it can be used for preliminary design of offshore oil jackets which are intended to be reused in the future. Morrison [17] compared two models, one of an offshore oil jacket platform on the UK continental shelf (UKCS) and one of the same platform with a wind turbine retrofitted on the jacket, using finite element analysis (FEA) with extreme wind and wave loads acting on the turbine. The Leman BH platform was selected for modelling as it was found to be the representative of more than 300 offshore oil and gas platforms on the UKCS in respect of jacket type, topside weight and water depth, based on the database analysis of such platforms. The FEA results show that the retrofit would be possible since all the jacket members will experience an average stress decrease of 35% in legs, and the pile loadings would reduce by 30% on average [17]. Although the study results can be applied to 128 platforms in the UKCS, wind and wave forces were only considered in the perpendicular position to a face of the platform [17], while they can affect the platform at any angle. A model for the conversion of offshore oil and gas platforms into sites for generating renewable energy, including wind energy, was established by a project called RELife (Renewable Energy for a new Life of offshore platforms), which was based on the techno-economic-environmental analysis of different options for the reuse [2]. As presented by Leporini et al. [2], the technical scenarios and the environmental and economic feasibility of the two types of platforms (one 4-legged platform with 3 production wells and one 4-legged platform with 4 production wells) were evaluated in the context of the Adriatic Sea and the North Sea [2]. The study shows that the platform in the Adriatic Sea is more suitable for developing a solar photovoltaic floating park, given limited wind energy resources, while the one in the North Sea, with the existence of a wind farm nearby, is more appropriate for producing wind energy [2]. Since key technical, economic and environmental criteria are considered in the regional context, the RELife model can be used to inform the decision-making process of decommissioning options; however, other considerations can be included, such as the presence of investment firms [2].

Relevant topics focused on retrofitting measures, expert opinions, and platform concepts. Delving into retrofitting solutions for converting offshore oil and gas structures into support structures for horizontal and vertical axis wind turbines, Mendes et al. [18] presented five retrofitting solutions, four of which are relating to the substructure, particularly crown pile configuration, long pile, mooring lines, and stirrups, and one is associated with modifying the wind turbine from 5 MW to 2 MW. The analysis showed that the 2 MW model is the only solution that satisfies the safety conditions [18]. Fowler et al. [19] undertook a global survey involving environmental experts to guide best decommissioning practices in the North Sea. While the North Sea adheres to OSPAR Decision 98/3 which requires the complete removal of disused offshore installations, except under certain circumstances and with a permit from the competent authority [20], a strong consensus among experts (94.7%) was reached on a more flexible case-by-case approach to decommissioning that could benefit the regional environment. Partial removal options were regarded as delivering more desirable environmental outcomes than complete removal of platforms, but both approaches were equally supported in the case of wind turbines [19]. Thiagarajan and Dagher [21] conducted a review of floating offshore structure concepts for designing offshore wind farms. These concepts are mainly grouped into three categories based on their source of stability: (i) ballast stabilized (low center of gravity), e.g., spar, (ii) mooring stabilized, e.g., tension leg platform, and (iii) buoyancy or waterplane stabilized, e.g., semisubmersible, which were modifications of similar structures used in the offshore oil and gas industry. This shows the synergy between the two industries, and hence the potential for repurposing offshore oil and gas platforms for offshore wind turbines.

To the best of the authors' knowledge, no research studies have been undertaken to develop a decision-making framework for converting offshore oil and gas platforms into offshore wind turbines, which generalizes the critical aspects that need to be considered for such conversion, although some of those aspects such as technical, economic and environmental ones, have been analysed in the literature as mentioned above. It should be noted that in Ersdal et al.'s [22] monograph, these authors have extensively discussed the fundamental issues related to the ageing of offshore oil and gas structures and necessary considerations for life extension. Some of these issues and considerations are also presented in this paper, particularly technical aspects including corrosion protection, site conditions and loads acting on the structures, and the fatigue design. However, the corresponding issues and considerations examined by Ersdal et al. [22] are only relevant to the petroleum industry and were intended to help extend the service life of older offshore structures for oil and gas production. Whilst, the technical aspects investigated by the present research relate to both the petroleum industry and the wind power industry, with a comparison between the two industries, and aim to assist the retrofitting of existing offshore oil and gas jackets to offshore wind turbine substructures. Furthermore, the economic, environmental and legal aspects of the matter are discussed, and relevant recommendations are provided, particularly for petroleum operators and wind power developers.

3. Background

As the final stage in the offshore oil and gas lifecycle, decommissioning aims "to remove or otherwise satisfactorily deal with, in a safe and environmentally responsible manner, structures, equipment and property previously used to support activities in the offshore area" [23,24]. As identified by Ferreira and Suslick [25], the decommissioning process comprises the following four phases:

(i) *Plugging and abandonment*, which refer to tasks and actions, normally including placement of cement plugs in the wellbore, to isolate and protect the environment and all freshwater zones and surroundings from a source of potential inflow—a formation with permeability that may be a water or a hydrocarbon bearing zone [26,27];

(ii) *Pipeline decommissioning*, which can be undertaken in different ways, depending on national regulations: leaving in situ, total removal except for large diameter trunklines, or removal of specific pipeline sections after assessing the risk of obstructions and/or hazards to fishing [28];

(iii) *Platform decommissioning*, which in most regional and national legal frameworks refers to complete removal of the platform to shore for dismantling as the base case (where the dismantled equipment and materials will be recycled or reused and the associated hazardous and radioactive wastes will be handled) [29–33], as well as the retrieval or placement at a safe depth, below the mudline, of all casings, wellhead equipment, templates and pilings according to the regulations [20,25,34,35]; and

(iv) *Site clearance*, which involves removal of all obstructions, such as drill cuttings and shell mounds from the site to return the environment to its original pristine condition [25,36].

This study focuses on platform decommissioning, which can be categorized into three main approaches: complete removal, partial removal, and leave in situ. A platform comprises the topside, which is the structure containing all equipment, and the substructure, which consists of the parts between the topside and the seabed, or mudline [29]. For complete removal, while the topside must often be returned to shore for reuse, recycling or final disposal on land, the substructure must be severed 15 ft below the mudline, or to the level of the "footings" for steel installations weighing more than 10,000 t (excluding the topside), as required in the United States (US) and the UK, respectively [29,37]. While complete removal of the platform is required in most legal regimes, exceptions can be considered for partial or full retention of the platform, in cases where it is technically infeasible or unsafe to remove the platform, or if the retention demonstrates benefits, or subject to compliance with specific requirements of the relevant stakeholders [24,29,34]. For the partial retention option, normally the topside is removed and taken to shore for reuse, recycling, or disposal, while the substructure is repurposed into an artificial reef [23,38]. As mentioned earlier, some scholars have investigated the feasibility of reusing the substructure for offshore wind turbine development (for example, Barros et al. [3]; Bingol [11]; Baqery and Edalat [12]; Braga et al. [13]) and one was put into practice [10].

Depending on their functions and the water depth, offshore oil and gas platforms fall into two main categories: movable drilling platforms and fixed platforms for production [39]. Movable drilling platforms include (i) *drill-ships*, which are ships with the drilling unit installed in the middle of the ship deck to enable the drilling string to reach the sea floor at deep waters through the ship; (ii) *semi-submersible platforms*, which are designed similarly to submersible platforms but are only partially submerged and use water to fill the bottom hull for buoyancy; (iii) *jack-up rigs*, which are mobile drilling platforms made with a floatable deck with three or four legs lowered onto the seabed upon being towed to the drill site; and (iv) *drilling barges*, which are mostly used in shallow, inland waters [39]. Fixed platforms have a wide range of applications and are used in deeper and shallow waters, including (i) *SPAR platforms*, which are low motion floaters that can support drilling and production operations in deeper waters with flexible or steel catenary risers, and conventionally consist of a large cylinder tethered to the sea floor by cables and lines; (ii) *tension leg platforms*, which are evolved from semi-submersible platforms, consisting of a buoyant floating platform kept in position by pretensioned anchors fixed to the seabed with vertical mooring lines called tension legs; (iii) *compliant towers* which are fixed rigs similar to fixed platforms but consisting of a narrow tower attached to piled foundations on the seabed and extending up to the platform; and (iv) *jacket platforms*, which are normally used in shallow waters and supported by the steel space frame called a jacket which consists of a plate girder or deck truss structure supported by welded tubulars that are piled to the seabed [39]. The concepts of these platforms are illustrated in **Figure 1**.

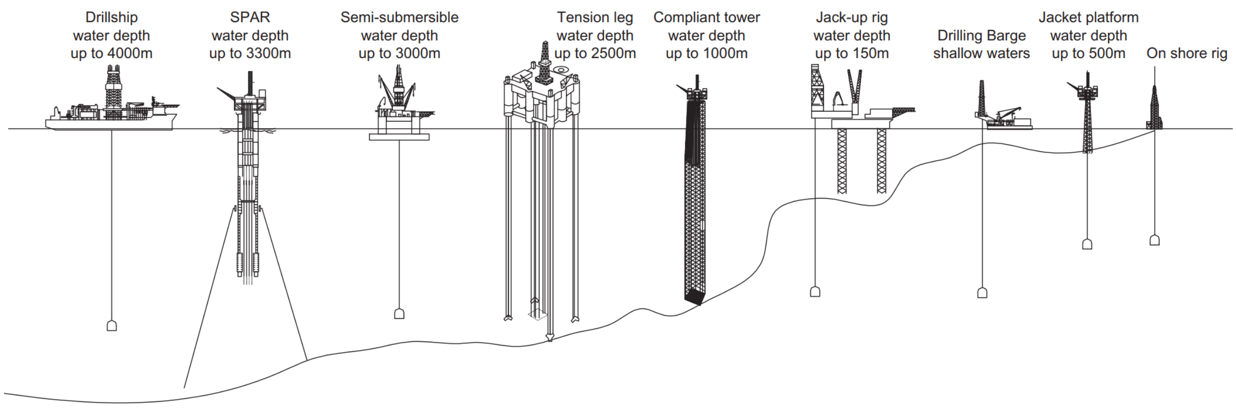

Figure 1. Different types of offshore oil and gas platforms used in different water depths [39].

Source: Reprinted from *Design and Analysis of Tall and Complex Structures*, Fu, Chapter 8: Design of Offshore Structures, p. 263, Copyright (2018), with permission from Elsevier.

An offshore wind turbine is constituted of a rotor-nacelle assembly, a support structure that consists of a tower, a substructure, and a foundation (see **Figure 2**). A synergy between the oil industry and the wind industry has been shown in the design of offshore structures [21,40]. In the wind industry, the offshore wind turbine substructure is designed according to site-specific characteristics, such as the water depth, wind/wave conditions, currents, seabed properties, and access requirements [40]. In general, offshore wind turbine substructure technology can be categorized into three major groups: shallow water, transitional water, and floating technologies [40]. Shallow water technologies are used to support offshore wind turbines in shallow waters, typically up to 30 m depth, including (i) *monopiles*, which are giant steel tubes potentially weighing over 500 t, presenting the simplest offshore wind substructure type; (ii) *gravity-based structures*, the oldest and simplest substructure type, which relies on the weight of a ballasted concrete base to provide stability; and (iii) *suction buckets*, which consist of a vertical steel skirt extending down from a horizontal base sucked into the soil surface [40,41]. Transitional water technologies are deployed in waters deeper than 30 m but shallower than 60 m, using multiple anchor points with typical types being jackets, tripods, and tri-piles [40,42]. A *jacket* is made up of four legs of more than 1 m in diameter connected with bracings, a working platform, a corrosion protection system, cables, and ladders [40]. *Tripods* and *tri-piles* are rarely used, due to not having proved to be cost-effective solutions for offshore wind [41]. The former consists of a central cylindrical section, bracings, and three supporting pile sleeves, while the latter consists of a single beam and three steel piles, which sit on a three-legged structure above the water surface [40]. In many instances, transitional substructures require higher costs and add incremental technology challenges compared to shallow water substructures [42]. Floating technologies may be more economical for deployment at deeper water sites, often more than 60 m, where larger fixed bottom structural dimensions are economically nonviable [40,42]. These technologies include (i) *spar buoy* (ballast-stabilized), which consists of a large deep draft floating cylinder with a low waterplane area, ballasted to keep the center of gravity below the center of buoyancy; (ii) *tension-leg* (mooring line-stabilised), of which positioning and stabilization are achieved through prestressed mooring lines/vertical tendons anchored to the seabed by suction piles; and (iii) *semi-submersible* (buoyancy-stabilised), which consists of multiple columns to provide hydrostatic stability and multiple pontoons to provide additional buoyancy [40,41]. The concepts of these substructure technologies are elucidated in **Figure 3**.

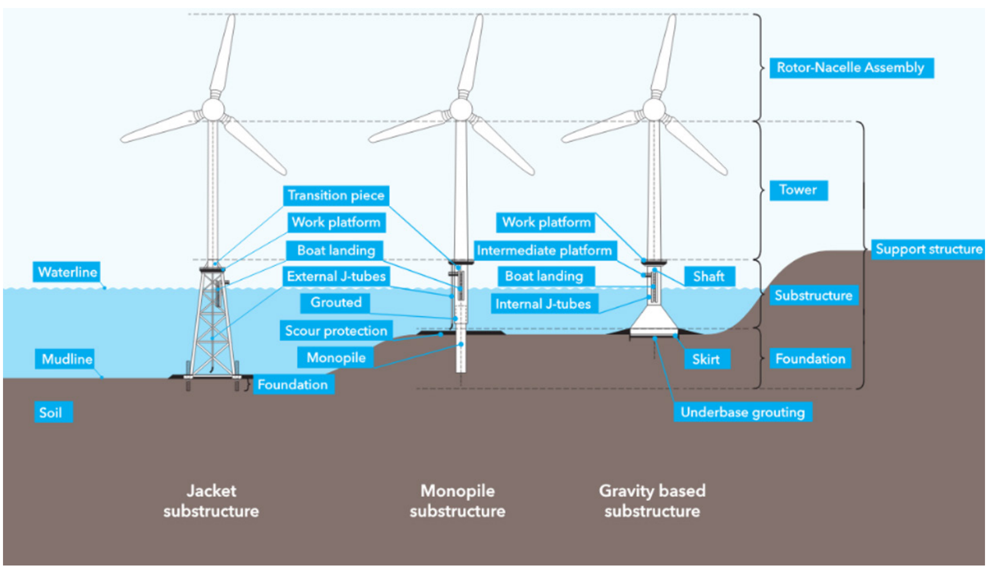

Figure 2. Offshore wind turbine components.

Source: Reproduced from DNV [43], reproduced courtesy of Det Norske Veritas.

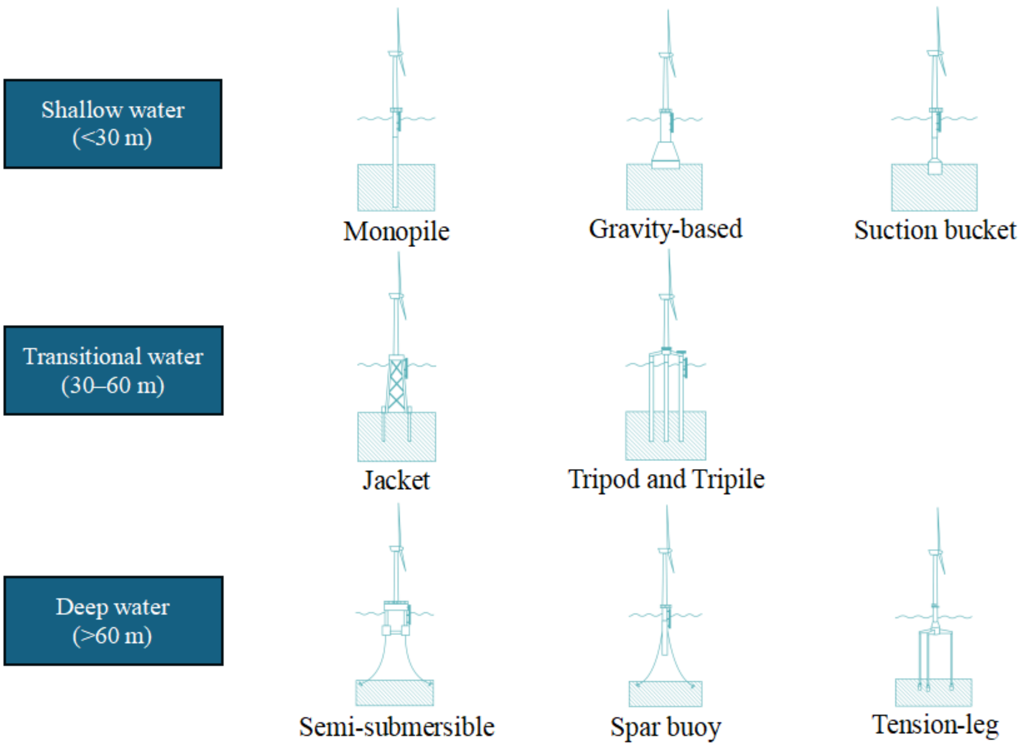

Figure 3. Substructure concepts for offshore wind turbines.

Source: Adapted from Empire Engineering [41], reproduced courtesy of Empire Engineering.

Most, if not all, of the research undertaken on repurposing offshore oil platforms for offshore wind turbines focused on fixed jacket platforms [3,10,12,17]. Converting offshore oil platforms into floating offshore wind turbines will induce completely different offsetting decommissioning costs [13]; therefore, it may not be the cost-effective option. Given the synergy between the substructures of offshore oil jacket platforms and offshore jacket wind turbines, there is potential for repurposing the offshore oil jacket as the substructure for the offshore jacket wind turbine (considering that the foundation of the wind turbine, as delineated in **Figure 2**, is inherently attached to the substructure and included in the offshore oil jacket). The fundamental difference between the two industries lies in the water depth considerations: while the water depth greater than 50 m is considered as "deep" by the wind industry, it is regarded as "shallow" in the oil industry, which has optimized designs for deeper waters [21], as demonstrated in **Figure 1**. In the wind industry, monopiles have been the dominant offshore wind substructure option throughout the world so far due to entailing low costs, minimal footprints on the sea floor, and minimal design requirements for transition from onshore to offshore [40]. Compared to monopiles, jackets are more complex and labor-intensive to fabricate and install; however, they are stiffer structures and more tolerant of varied geotechnical conditions [41]. While offshore wind jackets are often employed in the water depths of between 40 m and 100 m, jacket structures are usually applied by the offshore oil and gas industry at water depths much greater than 100 m [39,40,41]. Therefore, if offshore oil jackets can be reused as substructures for wind turbines, wind operators can benefit from higher wind speeds and resulting increased wind energy production (see the analysis in Section 4.2). Additionally, when employing wind turbines at deeper water sites, the visual impacts are minimized [40]. Furthermore, jacket platforms are one of the most common oil platforms in the world, accounting for around 95% of all global offshore oil platforms [39], making such conversion highly feasible in practice. Regarding offshore oil decommissioning, from the technical-economic perspective, when the structures are larger and located in deeper waters, they are more suitable to be left totally or partially intact, rather than being taken to shore for burial or reuse [3].

The wind farm development concept considered in this paper is based on the transformation of an offshore oil and gas field into an offshore wind farm. An offshore oil and gas field normally consists of central processing and living quarters platforms, and several wellhead platforms of the jacket type. An offshore wind farm consists of several wind turbines and, if located far away from the coastline, a substation for the transformation of the electricity from alternating current (AC) produced by the wind turbines to direct current (DC) to minimize power losses when sending the electricity in a subsea power cable to shore. The central oil and gas platform could be used to support the substation, while the wellhead platforms could be the support structures for the wind turbines. Additional wind turbines could be installed to ensure efficient wind farm development. In this paper, the transformation of the jacket structures to support structures for wind turbines is given the main attention.

4. Considerations for the Conversion of Offshore Oil and Gas Platforms into Offshore Wind Turbines

This section synthesizes the technical, economic, environmental and legal aspects associated with the conversion of offshore oil and gas platforms into offshore wind turbines, particularly oil jacket structures into jacket wind turbine substructures.

4.1. Technical Aspects

4.1.1. Corrosion Protection

According to DNV's recommended practice for the corrosion protection of support structures of offshore wind farms (DNV-RP-0416), methods for corrosion control include corrosion allowance, cathodic protection (CP), corrosion protective coatings, and corrosion-resistant materials [44]. These methods should be applied appropriately in specific zones as delineated in **Figure 4**. The *atmospheric zone* is the external region exposed to atmospheric conditions; the *splash zone* is the region where external or internal surfaces of a structure are intermittently wetted by tides or waves or both; and the *submerged zone* consists of the region below the lower limit of the splash zone, including the scour zone and the zone of permanently buried structural parts [44]. Application of the corrosion protection methods for each zone is summarised in **Figure 5**, while guidance on such methods for offshore oil and gas platforms and offshore wind turbines is presented in **Table 1**.

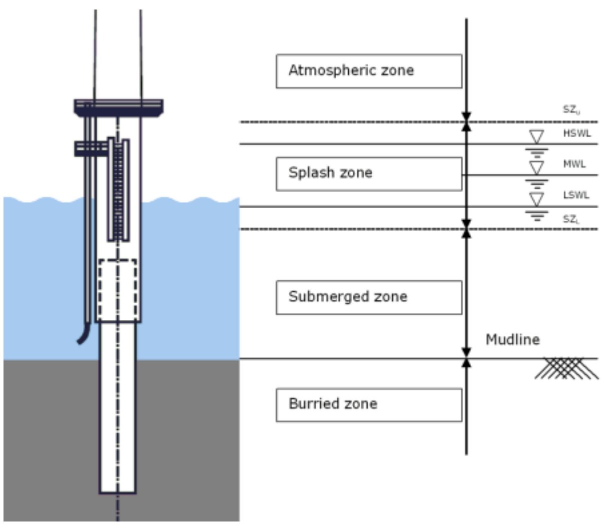

Figure 4. Schematic representation of levels and zones in the seawater environment.

Note: SZu: upper limit of the splash zone; HSWL: highest still water level; MWL: mean water level; LSWL: lowest still water level; SZL: lower limit of the splash zone.

Source: Reproduced from DNV [44], reproduced courtesy of Det Norske Veritas.

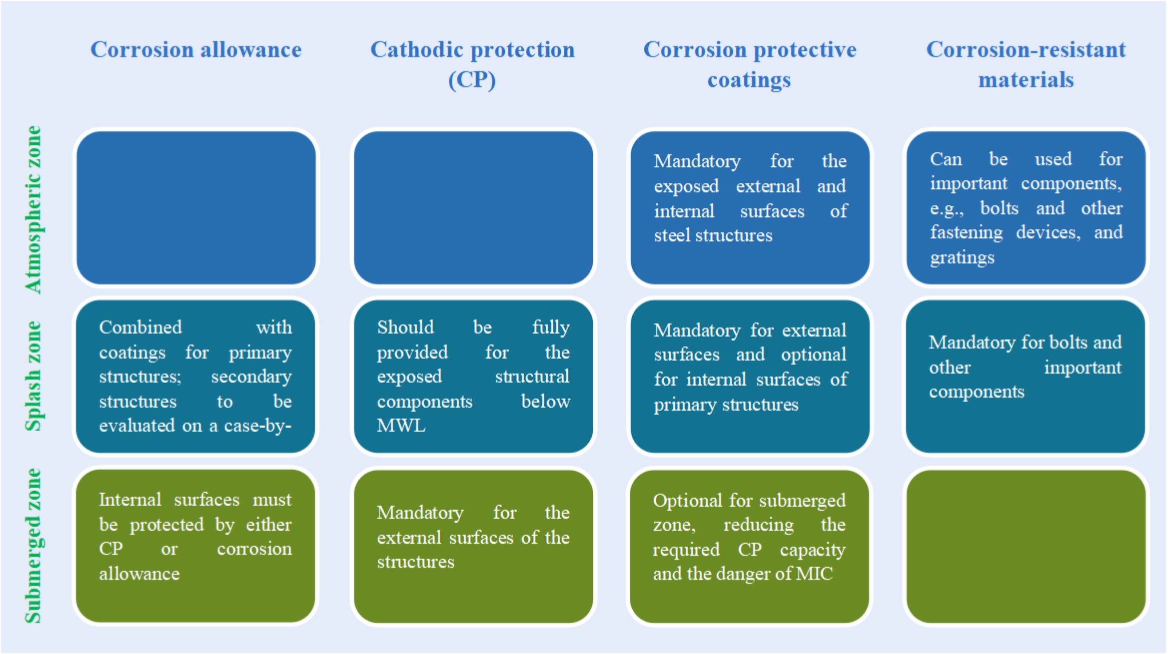

Figure 5. Corrosion protection for offshore wind turbines.

Note: MIC: microbiologically influenced corrosion.

Source: Created from the text in DNV [43,44], reproduced courtesy of Det Norske Veritas.

Table 1. Corrosion protection methods for offshore oil and gas platforms and offshore wind turbines.

Corrosion Protection Method	Description and Key Considerations
Corrosion allowance	When corrosion allowance is required as part of the corrosion protection, the corrosion allowance must be considered in the structural design for all limit state analyses through appropriate reduction of nominal thicknesses [44]. The 2 mm corrosion allowance normally applied to replaceable secondary structures of offshore wind turbines in the splash zone is usually not adequate for a minimum 20-year service life, so possible replacement of corroded components may be considered [43,44].
Cathodic protection (CP)	CP prevents localized forms of corrosion and uniform corrosion attacks [45]. In general, galvanic anode cathodic protection (GACP) is preferred for offshore wind turbine structures [44]. In GACP systems, galvanic anodes are designed to be oxidized and dissolved over their lifetime as part of a galvanic cell, preventing oxidation of the structural steel, which is why they are usually called "sacrificial anodes" [46]. Compared to GACP, impressed current cathodic protection (ICCP) systems, which use an active current to protect steel structures from corrosion, may be more advantageous but more vulnerable to environmental damage and third-party damage [44,46]. For GACP design, DNV's recommended practice for wind turbines (DNV-RP-0416) is compatible with that for fixed offshore oil and gas platforms (DNV-RP-B401), for example, anodes not to be located closer than 600 mm to nodes [44,45]. DNV-RP-0416 further requires anodes to be uniformly distributed, where reasonably practicable; anodes for the splash zone to be located at the upper level of the immersed zone; and anodes on legs to face the center of the structure [44]. Normally, the anode design life of fixed offshore oil and gas structures is at least equal to the design life of the structure [45]. Thus, when an offshore oil jacket is converted into an offshore wind turbine substructure, the CP may need to be retrofitted. For fixed offshore oil and gas structures intended to be reused for offshore wind turbines, provisions for retrofitting should be made during the initial design and fabrication [45].
Corrosion protective coatings	There are similarities between the guidelines for corrosion protective coatings of fixed offshore oil and gas platforms and wind turbines (DNV-RP-B401 and DNV-RP-0416, respectively), some of which include: (i) Using non-metallic or organic coatings can significantly decrease the CP current demand of the structures, and in combination with CP, will culminate in efficient and most cost-effective corrosion control; (ii) Coatings should be used where there is high demand for CP of bare metal surfaces, including deep water structures on which the formation of calcareous deposits may be slow; (iii) Coatings may not be appropriate for parts of submerged structures that require frequent inspection for fatigue cracks, for example, critical welded nodes of jacket structures [44,45].
Corrosion-resistant materials	Aluminum alloys or steel are commonly accepted for the towers and foundations of wind turbines. For a small wind turbine, aluminum alloys, particularly AA 3103 and AA 5052, which are cost-effective, are normally utilized to reduce the production cost; whereas for a large turbine, structural steels such as weathering steels, also known as atmospheric corrosion-resistant steels, are employed, as higher structural strength is essential [47]. In addition, aluminum and stainless steels are frequently utilized for mechanical engineering components, for example, fasteners, coolers, and brackets [48]. The use of corrosion-resistant materials is also highly dependent on the environment and the area of the offshore structure [49]. In the splash zone, which is the most severely corroded area where CP is ineffective and the use of corrosion-resistant materials or paint is inadequate, high corrosion-resistant materials such as super stainless steel and/or titanium are occasionally employed [44,49]. Material standards, for example, those of the American Society for Testing and Materials (ASTM) that apply to both industries, or the API for offshore oil and gas structures, should be exploited to specify the appropriate corrosion-resistant materials [44,50].

4.1.2. Site Conditions and Loads

- **Site Conditions Acting on Fixed Offshore Platforms and Offshore Wind Turbines**

Based on API Recommended Practice 2A-WSD, DNV-ST-0437, and IEC 61400-3-1, the site conditions that can affect loads on fixed offshore platforms and offshore wind turbines during the construction and operation phases are integrated in **Table 2**, with those similar between fixed offshore platforms and offshore wind turbines being arranged in the same rows. The main sources of environmental loading on offshore oil and gas platforms are winds, waves, tides and currents [50]. Likewise, winds, waves, currents and water levels form the primary basis for specifying the loads on offshore wind turbines [51]. All the meteorological and oceanographic conditions should be considered in normal and extreme states when designing offshore oil and gas platforms and offshore wind turbines [50,51].

Table 2. Loading conditions on fixed offshore platforms and offshore wind turbines (created from the text in API [50], DNV [51], IEC [52], reproduced courtesy of the American Petroleum Institute, Det Norske Veritas and International Electrotechnical Commission).

Loading Conditions	Fixed Offshore Platforms	Offshore Wind Turbines
Meteorological Conditions	Wind	Wind
	Others (normal and extreme air temperatures)	Others (air density, normal and extreme air temperature range, lightning, solar radiation)
Oceanographic Conditions	Waves	Waves
	Currents	Sea currents
		Water level
	Marine growth	Marine growth
	Ice	Sea/lake ice
	Scour	Seabed movement and scour
	Tsunamis, earthquakes, faults, seafloor instability	Seismic conditions
	Others (tides, storms, sea temperatures, precipitation, fog, wind chill)	Others (water density, normal and extreme sea temperature, seawater salinity, weather windows)
Others		Electrical network conditions
		Chemically active substances
		Mechanically active particles

For offshore platforms, wind conditions have effects on the structural components above the water, as well as any equipment, deck houses, and derricks installed on the topside [50]. Wind turbines are impacted by large aerodynamic loads [51]. Thus, according to DNV-ST-0437 and IEC 61400-1, it is necessary to understand normal wind conditions, which usually take place during normal operation of a wind turbine, and extreme wind conditions, which occur in a 1-year or 50-year return period, respectively [51,53].

Waves have irregular shapes and various heights, lengths, and propagation speeds, and can approach offshore oil platforms or offshore wind turbines from one or more directions concurrently [50,52]. Like winds, normal wave conditions and extreme wave conditions with 1-year and 50-year return periods must be considered for the safe design of offshore wind turbines [51].

- **Loads Acting on Fixed Offshore Platforms and Offshore Wind Turbines**

Following API Recommended Practice 2A-WSD, the loads specified in **Figure 6** and the associated dynamic impacts should be considered when establishing the design loading conditions for fixed offshore platforms [50]. Fixed offshore platforms should be designed for suitable loading conditions that generate the most severe impacts on the structure and should be a combination of environmental conditions with suitable dead and live loads [50] as demonstrated in **Figure 7**. The loads exerted on offshore wind turbines, according to DNV-ST-0437, are presented in **Figure 8**. Like fixed offshore platforms, offshore wind turbines must be designed with the most negative impact of loading on the structure, considering the related probability level [51]. Research suggests that when offshore wind turbines are exposed to combined wind-wave loading, turbulent wind mainly induces tower-top displacement, while the impact of wave loading is relatively insignificant; however, wind-induced vibrations at the tower top can be partly lessened by waves [54]. Under the combination of wind and wave loads, environmental variability, especially intensifying aerodynamic loads, can escalate the risk of structural buckling of offshore wind turbines [54].

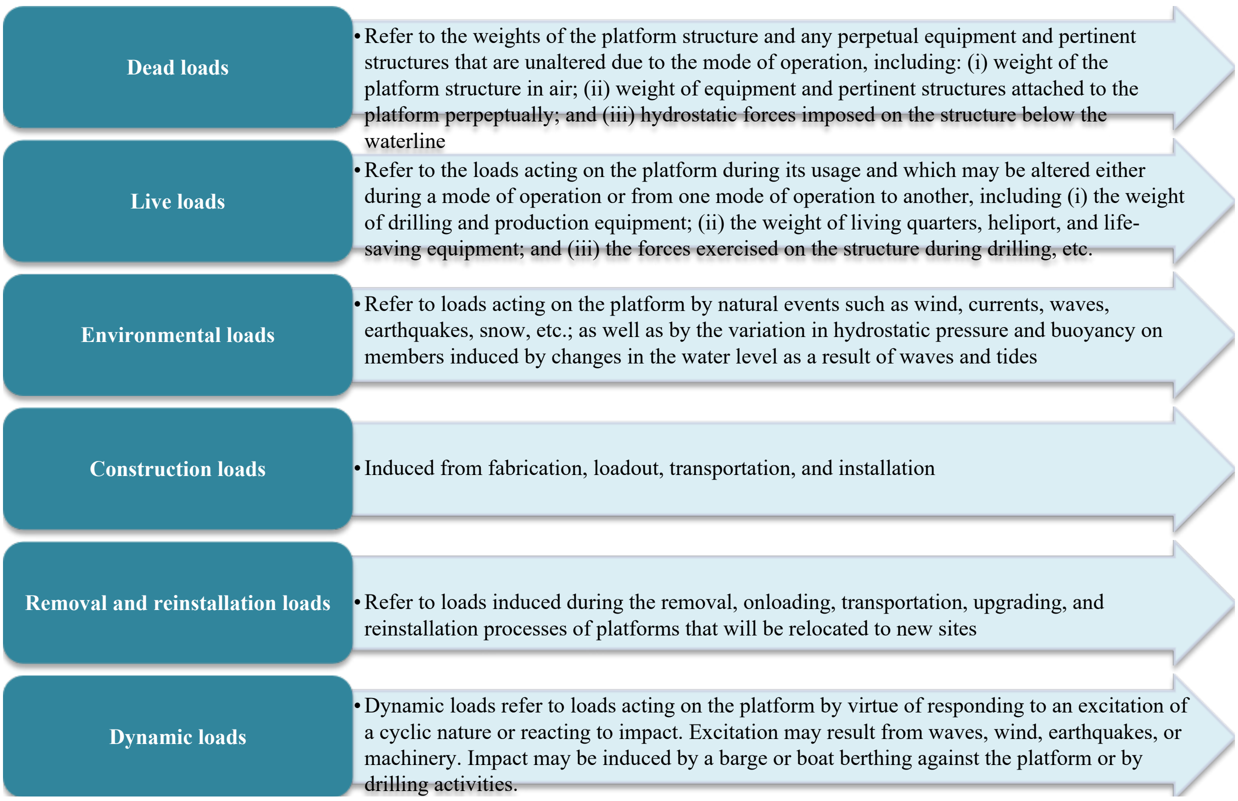

Figure 6. Loads acting on fixed offshore platforms.

Source: Created from the text in API [50], reproduced courtesy of the American Petroleum Institute.

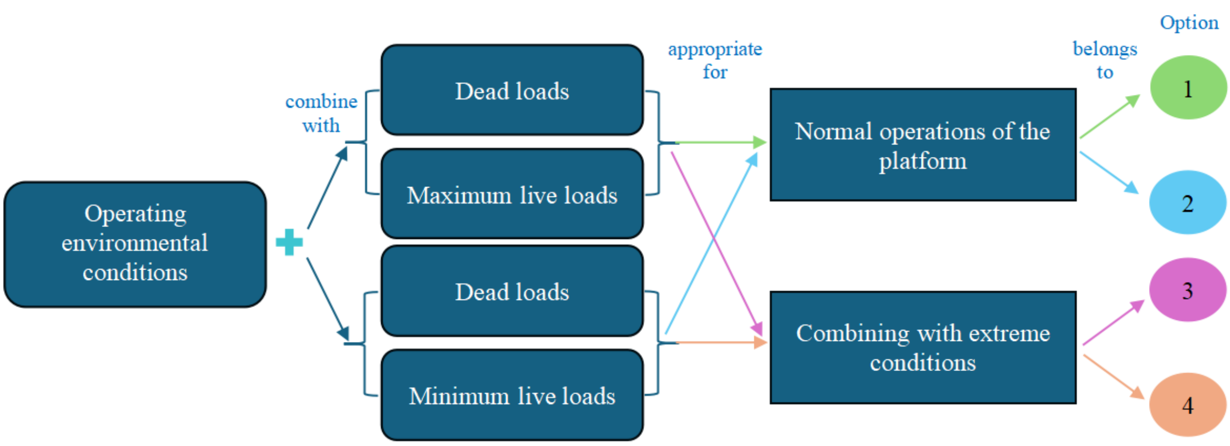

Figure 7. Design loading conditions for fixed offshore platforms.

Note: The color of the arrow termed 'appropriate for' corresponds to the color 'belongs to' and the color of the related option.

Source: Created from the text in API [50,55], reproduced courtesy of the American Petroleum Institute.

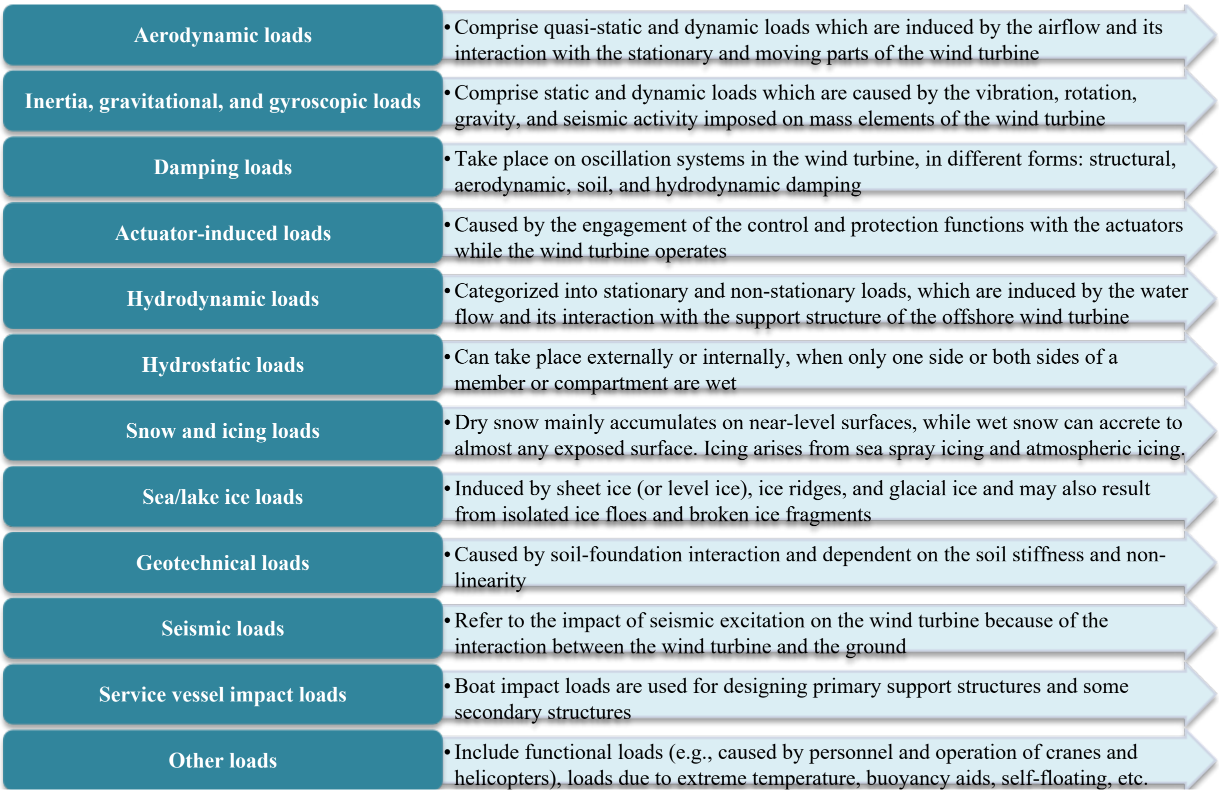

Figure 8. Loads acting on offshore wind turbines.

Source: Created from the text in DNV [51], reproduced courtesy of Det Norske Veritas.

4.1.3. Fatigue Design

API Recommended Practice 2A-WSD provides specific guidance for the fatigue design of fixed offshore platforms [50]. DNV-ST-0126 provides specific technical provisions and acceptance criteria for the fatigue design of offshore wind turbines [43]. Meanwhile, the guidance on methods for fatigue assessment of offshore steel structures and structural components, as indicated in DNV-RP-C203, can apply to both fixed offshore platforms and offshore wind turbines [56]. The critical consideration for the fatigue design of fixed offshore platforms and offshore wind turbines is the design fatigue life of the structures.

- **Fixed Offshore Platforms**

According to API Recommended Practice 2A-WSD, the design fatigue life of each joint and member in fixed offshore platforms must not be less than the intended service life of the structure multiplied by a safety factor [50]. For in-situ conditions, the safety factor for fatigue of steel components must depend on the failure consequence (i.e., criticality) and in-service inspectability [50]. **Table 3** presents the fatigue life safety factors for Category L-1 structures, noting that critical elements are those whose sole failure could be catastrophic. For Category L-2 and L-3 conventional steel jacket structures, a reduced safety factor of 1.0 should be applied to redundant diver or ROV (Remotely Operated Vehicle) inspectable framing, whereas safety factors for other cases should be reduced by half of those in the table [50]. Determination of Category L-1, L-2, and L-3 structures is indicated in **Table 4**.

Table 3. Fatigue life safety factors (consolidated from API [50], reproduced courtesy of the American Petroleum Institute).

Exposure Category	Failure Critical	Inspectable	Not Inspectable
L-1	No	2	5
L-2 and L-3		1 (also applies to a redundant diver or ROV)	2.5
L-1	Yes	5	10
L-2 and L-3		2.5	5

Table 4. Exposure Category Matrix (API [50], reproduced courtesy of the American Petroleum Institute).

Life Safety Category	Consequence Category		
	C-1 (High Consequence)	**C-2 (Medium Consequence)**	**C-3 (Low Consequence)**
S-1 (manned-non-evacuated)	L-1	L-1	L-1
S-2 (manned-evacuated)	L-1	L-2	L-2
S-3 (unmanned)	L-1	L-2	L-3

Note: L-1 represents the highest exposure level, L-2 refers to the intermediate exposure level, and L-3 is the lowest exposure level [57]. See definitions of platforms categorized as S-1, S-2 and S-3 in API [50].

- **Offshore Wind Turbines**

As provided under DNV-ST-0126, the design fatigue life for structural components should be based on the expected service life of the structure [43]. The full-service life of the structure is defined as the sum of (i) the time between installation of the support structure and installation of the wind turbine, (ii) the time between installation and operation, and (iii) the operation time for the wind turbine. If a service life is not defined, 20 years should be used [43]. Fatigue calculations may be based on a steel wall thickness equal to the nominal thickness, deducted by half the corrosion allowance over the full-service life of the structure [43].

For both fixed offshore platforms and offshore wind turbines, there are uncertainties associated with fatigue life calculations. Therefore, reliability methods may be utilized to demonstrate the impact of uncertainties on the probability of a fatigue failure [56].

4.2. Economic Aspects

The comparison between the complete removal and the offshore wind turbine options for decommissioning the jacket of the offshore platform named "Ilam" in the Persian Gulf shows that the latter would reduce the total decommissioning cost by 22.79% and save nearly 9 million US dollars for the operator [12]. The items for which the costs would be reduced include Platform Removal, Platform Preparation, Power Cable Removal, Site Clearance, Weather Contingency, Miscellaneous Work Provision, Mobilization and Demobilization of Derrick Barges, Materials Disposal, and Project Management, Engineering and Planning [12].

A cost-benefit analysis should compare the construction of a completely new offshore wind turbine with the development of an offshore wind turbine using a retrofitted offshore oil jacket. Following the *2024 Cost of Wind Energy Review* published by the National Renewable Energy Laboratory, the LCOE value of a 2023 referenced fixed-bottom offshore wind plant in the US was estimated at $117/MWh, of which 23.9% was constituted by the Turbine section, 35.5% by the Balance of System CAPEX section (including array system, export system, installation, lease price, offshore substation, project development, scour protection, and substructure), and 13.7% by the Financial CAPEX (including procurement contingency, installation contingency, commissioning, construction insurance, construction financing, and decommissioning), and 26.9% by the Operational Expenditures (OPEX) (including operations and maintenance) [58]. Since the installation and substructure costs represented significant components of the Balance of System CAPEX at 13.1% and 12%, respectively [58], conversion of a fixed offshore oil platform into a fixed-bottom offshore wind turbine can make a significant saving of such costs. However, as OPEX also accounted for a large portion of the LCOE (26.9%), OPEX should be compared between repurposing a fixed offshore oil platform and constructing a completely new fixed-bottom offshore wind turbine. This is due to the uncertainties associated with an offshore wind turbine during its operations and maintenance, including disruptive external events and component failures [59], which may cause significant damage to an offshore wind turbine with a substructure reused from a retired oil platform. Disruptive external events refer to external natural events (i.e., earthquakes, storms, rogue waves, etc.) or man-made events, such as terrorist acts or collisions with ships [59]. An offshore wind turbine consists of many components that constitute the rotor-nacelle assembly and the support structure [43]; each component has three different failure modes that determine a minor repair, a major repair, or a replacement [59]. Since components are interconnected, the failure of a single element will lead to the failure of the whole system and a halt in production [59].

Sim's study [60] demonstrates that the economic value of potential offshore wind farms on the mid-west coast of South Korea is predominantly influenced by the investment cost and sales amount, i.e., an increase in the investment cost will result in a decrease in the economic value of the potential sites, while an increase in energy production will lead to an increase in the economic value of potential sites. While reusing an offshore oil jacket to develop an offshore wind turbine will inherently reduce the investment cost (for example, the installation and substructure costs as mentioned above), a comparison of the energy production between this option and the option of constructing a completely new offshore wind turbine should be undertaken. Energy production from offshore wind turbines is largely determined by a combination of water depth, wind speed, wind energy density, and turbine capacity [60]. Wind energy is more intense and consistent in areas with greater water depth, where wind speeds are generally higher and more persistent [61,62]. Pang et al.'s analysis [63] shows that the higher the wind speed, the greater the effects on the increase of wind power. Wind speed and turbulence have a powerful impact on wind turbine performance at a height of up to 160 m [64]. Wind energy density is proportional to the cube of wind speed [65,66] as well as the wind power [64]. Akhtar et al.'s study [67] found that substitution of larger wind turbines (15 MW) for smaller ones (5 MW) enhanced the capacity factor by 2–3%. Capacity factor is the ratio of average output electrical power to rated electrical power of the wind turbine, and a higher capacity factor implies a higher output power compared to the rated power of the wind turbine [68,69]. The capacity factor is generally derived from the wind speed [70]. Therefore, when offshore wind turbines are developed from offshore oil jackets, they can benefit from the greater water depth, as well as the higher wind speed, wind energy density, and capacity factor, which are associated with more wind energy production.

4.3. Environmental Aspects

Repurposing offshore oil jackets into offshore wind turbines means that the offshore oil jackets are retained as artificial reefs. The structural intricacies of the jacket structures offer a framework for the formation of robust artificial reefs, which emerge as the localized biodiversity hotspots over the lifetime of the structures [71,72]. Complete removal of offshore oil and gas platforms will remove the unique artificial ecosystems that have developed over decades of coexistence with the marine environment [72].

The RTR program was originally developed by the then Minerals Management Service of the US Department of the Interior to convert decommissioned offshore rigs, particularly the steel jackets of fixed rigs, into artificial reefs, with the first RTR program taking place in 1979 off the coast of Florida [73]. The RTR program was expected to achieve a "win-win" outcome: (a) facilitating benthic habitat conservation and fishery management, and (b) providing appreciable cost savings for oil and gas operators [73]. From an ecological perspective, offshore oil and gas structures as artificial reefs can make the following contributions: (i) provision of reef habitat, (ii) productivity of offshore ecosystems, (iii) enhancement of biodiversity, (iv) protection of the seabed from trawling, and (v) enhancement of connectivity [74].

4.3.1. Provision of Reef Habitat

Research found that the shallow sections of offshore structures host species such as mussel beds (*Mytilus edulis*) and other fauna that are not present naturally in the marine environment, while the deeper sections, which include the rock dump around the steel platforms, are more analogous to natural rocky reefs [74,75]. Notably, the artificial habitats provided by offshore structures may resemble protected natural habitats and even host species of conservation interest in the North Sea [74]. However, the complex fouling communities on artificial reefs may promote habitat-limited native species such as jellyfish and *Gambierdiscus*, the causative agent of ciguatera fish poisoning, which affects the ecological and economic health [76].

4.3.2. Productivity of Offshore Ecosystems

Research studies have demonstrated that offshore structures, such as artificial reefs, could enhance biomass production by increasing settlement, food, and sheltering opportunities [73,74]. The reef habitats associated with offshore structures may act as nurseries for marine species, for example, animals which feed on plankton, lumpsucker fish (*Cyclopterus lumpus*), two-spotted gobies (*Gobiusculus flavescens*), etc., which facilitate reproduction and contribute to enhanced production [73,74,77]. Nevertheless, while artificial reefs may reduce the mortality of juvenile fish by providing food or shelter [78], they may increase the mortality of juvenile fish by attracting predatory fish [79]. Gallaway et al.'s [80] study suggests that the protective habitats from offshore oil and gas platforms are particularly important for red snapper of younger ages compared to open habitats.

4.3.3. Enhancement of Biodiversity

The installation of offshore structures in a soft-sediment environment leads to a localized increase in species richness and diversity through colonization by reef-associated taxa [74]. Marine life assemblages on offshore oil and gas platforms with distinctive biodiversity have been found in many parts of the world, such as the Gulf of Mexico, the North Sea, the Arabian Gulf, and the South China Sea offshore Malaysia [75,81–83]. Research has found that marine growth thickness on offshore oil and gas structures is proportional to biological diversity [84]. Fortune et al.'s study [71] revealed that offshore oil and gas structures particularly contribute to local biodiversity where hard substrata are introduced to areas dominated by depositional (mud and sand) habitats. However, biodiversity related to offshore structures may be regarded as "artificial" [74]. Species composition on artificial reefs differs from natural reefs, which mostly depends on the depth, location effect and habitat type [75]. In addition, while rocky substrates hold the most species-rich communities, overall biodiversity is greatly influenced by keystone species, particularly *Mytilus edulis*, *Psammechinus miliaris,* and *Tubulariidae* [75]. Although the presence of non-native species may increase local species richness, this is usually not regarded as an added value [74].

4.3.4. Protection of the Seabed from Trawling

Offshore oil and gas structures also play a crucial role in habitat conservation, given the "de facto marine protected areas" formed from the rig's large internal space and the safety exclusion zone to be created in a radius of 500 m from the rig, which prohibits fishing [73,77,85,86]. The safety exclusion zones around the structures have also been found to have a positive effect on fish diversity [87]. Note that if offshore oil jackets are repurposed for offshore wind turbine substructures, the safety or exclusion zone surrounding the jacket structure will continue to persist, although the safety distances differ among countries [88].

4.3.5. Enhancement of Connectivity

Offshore structures may function as the "stepping-stones" for native species (for example, the mollusc *Mytilus edulis*) as well as non-native and invasive species (such as *Tubastrea* cup corals and lionfish) [75,76]. The stepping effect is crucial for both native and non-native species, since those able to colonize structures near the edges of their distributional range could then distribute to regions that would be out of reach otherwise [74]. Macreadie et al. [73] posited that artificial reefs in deep water may enhance ecological connectivity, leading to critical biographical consequences such as increased genetic homogeneity and decreased opportunity for allopatric speciation, which may have positive or negative effects depending on the species. Atchison et al. [89] found the proportional correlation of the genetic homogeneity of some species in the Gulf of Mexico with the distance between the offshore oil and gas platforms and the natural reefs, but the level of genetic homogeneity could be different among the species. Whilst, from McLean et al.'s [90] point of view, offshore structures may provide novel selective environments for promoting the new genetic variation, which requires very low rates of dispersal for spreading and hence could be essential for the persistence or recovery of natural marine systems.

4.4. Legal Aspects

Legal considerations are a critical part of the decision-making process for reusing offshore oil jackets as substructures for offshore wind turbines. **Table 5** presents the international legal framework and the national legal frameworks of the UK, Australia and Vietnam for offshore oil and gas decommissioning. In general, the international legal framework requires abandoned or disused offshore installations to be completely removed [91], while they can be fully or partially retained subject to permits and the associated conditions or certain circumstances, such as causing no harm to other sea users and providing a new use [20,92–94]. Under the national legal frameworks of Australia and Vietnam, complete removal of offshore installations after completion of hydrocarbon production is compulsory [24]; however, alternatives to complete removal may be considered, providing that they deliver benefits when retained and fulfill other provisions [24,95,96]. In such cases, the Australian guideline requires well integrity and safety-related matters to be taken into account [24], while the Vietnamese circular stipulates that the petroleum installation still has usable functions and meets the requirements of quality inspection, retrofit, renovation, and damage repair (if any) to ensure the safety of the installation [34]. In Australia, deviation from complete removal may be sought by titleholders via an accepted environmental plan [35], and research will need to be undertaken to determine the potential impact of dumping a platform on the marine environment [97]. Meanwhile, reuse of offshore facilities at their end state for energy or other projects is the priority option in the UK, subject to discussion with the Oil and Gas Authority and the Offshore Petroleum Regulator for Environment and Decommissioning [37]. Especially, when being consulted about the decommissioning programme, the Oil and Gas Authority must provide guidance on alternatives to decommissioning the installation or pipeline, such as re-using or preserving it, as well as how to frame the decommissioning programme to minimize the costs [98,99].

Table 5. International and national legal frameworks for offshore oil and gas decommissioning.

Framework Category	Legal Instrument
International legal framework	*Convention on the Continental Shelf 1958*
	United Nations Convention on the Law of the Sea 1982
	IMO Guidelines and Standards for the Removal of Offshore Installations and Structures on the Continental Shelf and the Exclusive Economic Zone 1989
	1996 Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972 (London Protocol)
	OSPAR Decision 98/3
National legal framework	The UK
	Guidance Notes: Decommissioning of Offshore Oil and Gas Installations and Pipelines (2018)
	Petroleum Act 1998
	Energy Act 2016
	Australia
	Guideline: Offshore Petroleum Decommissioning (2022)
	Section 572 of the Offshore Petroleum and Greenhouse Gas Storage Act 2006 (OPGGS Act)
	Environment Protection (Sea Dumping) Act 1981
	Vietnam
	Petroleum Law No. 12/2022/QH15
	Decision No. 49/2017/QD-TTg on Decommissioning of Petroleum Installations
	Circular No. 16/2024/TT-BCT Regulating the Protection and Abandonment of Petroleum Drilling Wells and Decommissioning of Petroleum Installations

5. Case Study

To support the analysis of the technical, economic, environmental and legal aspects that need to be considered when repurposing offshore oil and gas platforms into offshore wind turbines, a case study was undertaken, with two offshore oil platforms on Vietnam's continental shelf being the cases. These platforms were selected for the case study analysis, given their readily available data, providing practical references for the feasibility of the conversion.

5.1. Platform X

Platform X was designed to operate at a water depth of 53 m. The wind speed at the platform location is described in **Table 6**, which was referenced to 10 m above the mean sea level (MSL). According to DNV-ST-0437, wind turbine classes I, II and III require the annual average wind speed to be 10 m/s, 8.5 m/s and 7.5 m/s, respectively [51]. The available data shows the hourly mean wind speed over the 1-year period, which is generally more reliable than a single annual wind speed mean, at the location of platform X is 14 m/s. Then, considering the wind conditions, it is suitable to develop wind energy from the platform with a wind turbine class I.

As designed, the marine growth thickness on the jacket of platform X is lower at the shallowest and deepest levels (MSL and the mudline, respectively) and higher at intermediate levels (elevations −4.6 m and −48.6 m, respectively) [101] (see **Table 7**). Such marine growth distribution might be proportional to the concentration of biomass and diversity in the jacket area [102].

Table 6. Wind speed at the location of platform X [100].

Wind Speed Value	Return Period		
	1-year	100-year	100-year Tropical Cyclone
Hourly Mean	14 m/s	19 m/s	25 m/s
One-minute Mean	17 m/s	23 m/s	30 m/s

Table 7. Marine growth distribution on the jacket of platform X [101].

Depth (m)	Marine Growth Thickness (mm)
MSL	51
Elevation −4.6	153
Elevation −48.6	102
Mudline	25

Platform X was designed based on the API Recommended Practice 2A-WSD (21st edition). The total load combination factor for the basic load of platform X's topside is presented in **Tables 8** and **9**. While **Table 8** shows the designed maximum topside load for the operation of platform X, **Table 9** reveals the designed maximum topside load in the storm and calm sea conditions, which correspond to Option 1 and Option 3 in designing loading conditions for fixed offshore platforms following API Recommended Practice 2A-WSD (see **Figure 7**). As can be seen in **Table 8**, the dead load and the maximum live load of the topside were designed for normal operations of platform X, considering the equipment operating weight, piping operating weight in different directions, crane operating weight, crane operating moment in different directions, instrumentation dry weight, safety operating weight, electrical dry weight, and wind loadings in different directions. According to the API Recommended Practice 2A-WSD (21st edition), maximum live loads for drilling and production platforms like platform X should take into account drilling, production and workover mode loadings, and any suitable combinations of drilling or workover operations with production [55], which were not clarified in the loading design for platform X. As presented in **Table 9**, the dead load and the maximum live load of the topside were designed for operations of platform X in storm conditions, considering wind loads in different directions. For designing wind loads in extreme conditions, the averaging recurrence times of extreme wind speeds should be projected apart from the directions [55]. In addition, for designing operations of platform X in extreme conditions, other environmental loads should be considered, including wave, current and earthquake loads [55].

Table 8. Topside load combination factor of platform X [103].

Load Case	Description	Basic Load Sum (kN)			Operating with Maximum Topside Load							
		Fx (kN)	Fy (kN)	Fz (kN)	OP01 0°	OP02 42.0°	OP03 90.0°	OP04 132.0°	OP05 180°	OP06 222.0°	OP07 270°	OP08 312.0°
1	Dead load	0.0	0.0	−1911.6	1.100	1.100	1.100	1.100	1.100	1.100	1.100	1.100
T2	Unmodelled structural dead weight	0.0	0.0	−1236.0	1.150	1.150	1.150	1.150	1.150	1.150	1.150	1.150
T3	Unmodelled secondary dead weight	0.0	0.0	−187.6	1.150	1.150	1.150	1.150	1.150	1.150	1.150	1.150
T6	Topside liveload	0.0	0.0	−4703.1	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
T8A	Equipment operating weight	0.0	0.0	−1079.8	1.200	1.200	1.200	1.200	1.200	1.200	1.200	1.200
T9A	Piping operating weight (−Z)	0.0	0.0	−2648.2	1.200	1.200	1.200	1.200	1.200	1.200	1.200	1.200
T9B	Piping operating weight (+Y)	0.0	659.2	0.0		0.669	1.000	0.743				
T9C	Piping operating weight (−Y)	0.0	−364.9	0.0						0.669	1.000	0.743
T9D	Piping operating weight (+X)	565.1	0.0	0.0	1.000	0.743						0.669
T9E	Piping operating weight (−X)	−565.1	0.0	0.0				0.669	1.000	0.743		
T10	Crane operating weight	0.0	0.0	−101.0	1.200	1.200	1.200	1.200	1.200	1.200	1.200	1.200
T11	Crane operating moment in (+X) direction	0.0	0.0	0.0		−0.669	−1.000	−0.743		0.669	1.000	0.743
T12	Crane operating moment in (+Y) direction	0.0	0.0	0.0	1.000	0.743		−0.669	−1.000	−0.743		0.669
T13	Instrumentation dry weight	0.0	0.0	−145.3	1.200	1.200	1.200	1.200	1.200	1.200	1.200	1.200
T14A	Safety operating weight	0.0	0.0	−29.7	1.200	1.200	1.200	1.200	1.200	1.200	1.200	1.200
T15	Electrical dry weight	0.0	0.0	−122.6	1.200	1.200	1.200	1.200	1.200	1.200	1.200	1.200
20	Storm wind @ +X direction	73.8	0.0	0.0								
21	Storm wind @ +Y direction	0.0	42.5	0.0								
22	Oper wind @ +X direction	22.0	0.0	0.0	1.000	0.743		−0.669	−1.000	−0.743		0.669
23	Oper wind @ +Y direction	0.0	12.7	0.0		0.669	1.000	0.743		−0.669	−1.000	−0.743
			Fx (kN)		587	436	0	−393	−587	−436	0	393
	Total Load Sum		Fy (kN)		0	450	672	499	0	−253	−378	−281
			Fz (kN)		−13395	−13395	−13395	−13395	−13395	−13395	−13395	−13395

Table 9. Topside load combination factor of platform X (continued) [103].

Load Case	Description	Storm with Maximum Topside Load								Calm Sea
		SX01 0°	SX02 42.0°	SX03 90.0°	SX04 132.0°	SX05 180°	SX06 222.0°	SX07 270°	SX08 312.0°	CS01
1	Dead load	1.100	1.100	1.100	1.100	1.100	1.100	1.100	1.100	1.100
T2	Unmodelled structural dead weight	1.150	1.150	1.150	1.150	1.150	1.150	1.150	1.150	1.150
T3	Unmodelled secondary dead weight	1.150	1.150	1.150	1.150	1.150	1.150	1.150	1.150	1.150
T6	Topside liveload	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
T8A	Equipment operating weight	1.200	1.200	1.200	1.200	1.200	1.200	1.200	1.200	1.200
T9A	Piping operating weight (−Z)	1.200	1.200	1.200	1.200	1.200	1.200	1.200	1.200	1.200
T9B	Piping operating weight (+Y)		0.669	1.000	0.743					
T9C	Piping operating weight (−Y)						0.669	1.000	0.743	
T9D	Piping operating weight (+X)	1.000	0.743						0.669	
T9E	Piping operating weight (−X)				0.669	1.000	0.743			
T10	Crane operating weight									
T11	Crane operating moment in (+X) direction									
T12	Crane operating moment in (+Y) direction									
T13	Instrumentation dry weight	1.200	1.200	1.200	1.200	1.200	1.200	1.200	1.200	1.200
T14A	Safety operating weight	1.200	1.200	1.200	1.200	1.200	1.200	1.200	1.200	1.200
T15	Electrical dry weight	1.200	1.200	1.200	1.200	1.200	1.200	1.200	1.200	1.200
20	Storm wind @ +X direction	1.000	0.743		−0.669	−1.000	−0.743		0.669	
21	Storm wind @ +Y direction		0.669	1.000	0.743		−0.669	−1.000	−0.743	
22	Oper wind @ +X direction									
23	Oper wind @ +Y direction									
		639	475	0	−427	−639	−475	0	427	0
	Total Load Sum	0	469	702	521	0	−273	−407	−303	0
		−13274	−13274	−13274	−13274	−13274	−13274	−13274	−13274	−13274

According to the API Recommended Practice 2A-WSD (21st edition), the recommended minimum safety factor for each joint and member is 2; that is, their design fatigue life should be at least twice the anticipated service life of the structure, while for critical elements, a larger safety factor should be applied [55]. The target fatigue life of platform X is 30 years, which is two (2) times the design service life (15 years) of the platform [104]. The dynamic spectral fatigue analysis of the platform conducted in 2008 shows that six (6) primary and five (5) secondary member-end connections of the jacket had the fatigue life of less than 30 years; therefore, weld profile control was suggested for such connections [104] (see **Table 10**). The API X′-X′ S-N curve was utilised as the basis for calculating the fatigue lives of the connections, while the API X-X S-N curve was used with weld profile control for the welds involved, considering branch thickness effects following the API [104]. This conforms to the API Recommended Practice 2A-WSD, as the X′-X′ curve can be applied for welds without profile control but fit in a basic standard flat profile, and with a branch thickness less than 16 mm [55]. Meanwhile, the X-X S-N curve can be applied for welds that have a branch thickness of less than 25 mm and under profile control [55]. In both cases, the allowable stress for greater wall thicknesses should be scaled down, corresponding to Equation (1) [55], which was applied for braces in X jacket:

$$Allowable\ Stress = S_0 \left\{ \frac{t}{t_0} \right\}^{-0.25} \quad (1)$$

where:

S_0 = allowable stress from the S-N curve,

t = branch member thickness,

t_0 = limiting member thickness.

The target fatigue lives of welded details in X jacket are presented in **Table 11**. In X case, for the joints that do not meet the target fatigue life after applying weld profile control, the recommended improvement is toe grinding with weld profile control, following which the fatigue life can be improved by a factor of 2.2 [104]. This also shows that the fatigue design of the welded details in X jacket is in accordance with the API Recommended Practice 2A-WSD (21st edition).

Table 10. Fatigue life details of the fatigue-sensitive joints on the jacket of platform X [104].

Joint No.	Brace Joint	Description	Fatigue Life API X′-X′	Fatigue Life API X-X	Remark
3022	622	Secondary Conductor Support @ EL(−) 8.566 m	29.92	119.67	Weld profile control
3022	612	Secondary Conductor Support @ EL(−) 8.566 m	24.86	93.53	Weld profile control
3020	682	Secondary Conductor Support @ EL(−) 8.566 m	25.01	93.77	Weld profile control
3020	672	Secondary Conductor Support @ EL(−) 8.566 m	28.29	114.34	Weld profile control
3021	652	Secondary Conductor Support @ EL(−) 8.566 m	27.19	105.48	Weld profile control
3012	3019	EL(−) 8.566 m Horizontal Bracing	26.39	144.63	Weld profile control
3013	3023	EL(−) 8.566 m Horizontal Bracing	28.42	155.72	Weld profile control
3033	2037	EL(−) 8.566 m Primary X Brace	11.60	41.92	Weld profile control
3033	3040	EL(−) 8.566 m Primary X Brace	26.76	136.07	Weld profile control
3030	2037	EL(−) 24.273 m Primary X Brace	14.58	53.53	Weld profile control
3030	1125	EL(−) 24.273 m Primary X Brace	15.01	55.60	Weld profile control

Table 11. Target fatigue lives of welded details in X jacket [104].

Exposure Category	Inspectable	Not Inspectable[1]
Welded details	2 × 15 years[2] = 30 years	4 × 15 years = 60 years

Note: [1] Welded details that cannot be accessed for inspection and repair, comprising: (i) primary joints at the mudline level; (ii) brace/ring intersections and other interior details of ring stiffened nodes; and (iii) the hidden welds of overlapping joints (if relevant). [2] Planned in-service fatigue life.

5.2. Platform Y

Platform Y includes two Wellhead Platforms (WHPs) Y1 and Y2, which will need to be completely removed according to the field decommissioning plan [105]. Details of the decommissioning costs for the complete removal of platform Y are tabulated in **Table 12.** As indicated in Baqery and Edalat's study [12], retaining the jacket of Ilam platform in the Persian Gulf for offshore wind energy development would reduce by half the costs of Platform Preparation, Mobilization and Demobilization of Derrick Barges, and Project Management, Engineering and Planning. By applying such factor to the decommissioning costs of platform Y and given that the boat landing and piles are part of the jackets of the WHPs Y1 and Y2, it can be assumed that the costs of items 4.1.1, 4.1.4 and 5.2 could be decreased by half, while the costs of items 4.3.2, 4.3.3, 4.4.2 and 4.4.3 could be deducted. Therefore, partial removal of platform Y could save about one seventh of the total decommissioning cost as originally planned (see **Table 12**).

Table 12. Decommissioning costs of platform Y [105] (with additional calculations from this study).

No.	Description	Day/Unit		Unit Rate (USD)	Sub-Total Cost (USD)	Total Cost (USD)	Cost Reduced by Retaining the Jackets Y1 and Y2
1	FPSO decommissioning					8,685,000	
1.1	Project management and design	1	Unit	1,175,000	1,175,000		
1.2	Contract management, hierarchy and insurance costs	1	Unit	155,000	155,000		
1.3	Mobilisation and fuel oil for maritime vehicles	1	Unit	430,000	430,000		
1.4	Compressors removal	1	Unit	345,000	345,000		
1.5	Subsea equipment removal	1	Unit	4,370,000	4,370,000		
1.6	Anchors and moorings removal	1	Unit	450,000	450,000		
1.7	Transit	1	Unit	45,000	45,000		
1.8	Decontamination and cleaning	1	Unit	1,095,000	1,095,000		
1.9	Seabed surveys	1	Unit	450,000	450,000		
1.10	Other costs	1	Unit	170,000	170,000		
2	Detailed Design/Environmental Impact Assessment/Surveys	1	Unit	2,500,000	2,500,000	2,500,000	
3	Well Plugging and Abandonment (P&A)					40,800,000	
3.1	Mobilisation of a drilling platform and maritime vehicles	4	Day	300,000	1,200,000		
3.2	Drilling platform preparation	1.5	Day	300,000	450,000		
3.3	Well P&A for Platform Y1	73	Day	300,000	21,900,000		
3.4	The drilling platform leaves Platform Y1 and approaches Platform Y2	3	Day	300,000	900,000		
3.5	Drilling platform preparation	1.5	Day	300,000	450,000		
3.6	Well P&A for Platform Y2	87	Day	300,000	26,100,000		
3.7	Demobilisation of the drilling platform and maritime vehicles	4	Day	300,000	1,200,000		
4	Decommissioning of WHPs Y1 and Y2, pipeline connectors, intra-field pipelines, Pipeline End Manifold (PLEM) and Pipeline End Termination (PLET) systems					45,390,000	
4.1	Decommissioning of WHPs Y1 and Y2 and intra-field pipelines, flushing and cleaning the topsides						
4.1.1	Mobilisation of cranes and maritime support vehicles	1	Unit	6,250,000	6,250,000		3,125,000
4.1.2	Shutting down/Flushing intra-field pipelines and the topsides, including manufacture of skidding equipment and receipt of support vessels	24	Day	60,000	1,440,000		
4.1.3	Topsides shutdown and flange installation	45	Day	40,000	1,800,000		
4.1.4	Preparation for removal of WHPs Y1 and Y2 (e.g., scaffolding, installing lifting and dismantling equipment, etc.)	60	Day	35,000	2,100,000		1,050,000
4.1.5	Manufacturing and welding lifting holes	2	Day	800,000	1,600,000		
4.2	Decommissioning of intra-field pipelines, PLEM and PLET systems						
4.2.1	Removal of pipeline connectors and installing flanges at the riser joints	5	Day	350,000	1,750,000		
4.2.2	Removal of PLEM and PLET systems	7	Day	350,000	2,450,000		
4.2.3	Retrieval of intra-field pipelines	30	Day	350,000	10,500,000		
4.3	Removal of WHP Y1						
4.3.1	Topside removal	10	Day	350,000	3,500,000		
4.3.2	Boat landing removal	2	Day	350,000	700,000		0
4.3.3	Cutting piles to 3 m below the seabed, and cutting the pedestal crane	12	Day	350,000	4,200,000		0
4.3.4	Site surveys	1	Day	350,000	350,000		
4.4	Removal of WHP Y2						
4.4.1	Topside removal	10	Day	350,000	3,500,000		
4.4.2	Boat landing removal	2	Day	350,000	700,000		0
4.4.3	Cutting piles to 3 m below the seabed, and cutting the pedestal crane	12	Day	350,000	4,200,000		0
4.4.4	Site surveys	1	Day	350,000	350,000		
5	Other costs					1,950,000	
5.1	Insurance	1	Unit	700,000	700,000		
5.2	Project management cost	1	Unit	1,250,000	1,250,000		625,000
	Total cost for complete removal of platform Y					99,325,000	
	Cost reduced by retaining jackets Y1 and Y2						14,600,000
	Total cost for partial removal of platform Y						84,725,000

Platform Y started oil production in 2014, with the jacket and intra-field pipelines designed to operate for 20 years. Therefore, if the platform is converted into an offshore wind turbine after cessation of oil production, it is assumed that offshore wind operations will commence on the platform around 2035, considering time for approval, platform decommissioning and wind turbine construction. According to the World Bank [106], the LCOE of a typical 10 MW fixed offshore wind turbine in Vietnam in 2035 is US$62/MWh and US$51/MWh, respectively, for low growth and high growth scenarios. As mentioned earlier, repurposing a fixed offshore oil platform for a fixed-bottom offshore wind turbine can save a considerable amount of the Balance of System CAPEX, thus the LCOE of platform Y will further be reduced. Nevertheless, a comparison of the OPEX between using a retrofitted offshore wind turbine on platform Y and a fully new one should be undertaken.

6. Discussion

6.1. Technical Aspects

6.1.1. Corrosion Protection

Comparison of DNV's recommended practice and standard on corrosion protection for fixed offshore oil and gas platforms and offshore wind turbines shows that the related recommendations or requirements for the two industries are mostly similar, although application of different corrosion control methods to specific zones of offshore wind turbines, as well as additional requirements for fixed offshore oil and gas platforms, such as those related to GACP design, should be taken into account to enable the conversion. This means the corrosion protection methods that have been used for the offshore oil jacket can be sufficient to continue preventing the jacket structure from being corroded under the operation as a wind turbine substructure, provided that the corrosion protection systems have been designed to cover more than the service life of the jacket structure, for example, the corrosion allowance for corroded components. It will be best if provisions for retrofitting are made during the initial design and fabrication of the offshore oil jacket, particularly the CP.

6.1.2. Site Conditions and Loads

- **Site Conditions**

In general, the environmental conditions to be considered for designing fixed offshore platforms are similar to those necessary to be taken into account in the design of offshore wind turbines. To enable the conversion of offshore platforms into offshore wind turbines, other conditions that influence offshore wind turbines must be considered, particularly electrical network conditions. As part of the design for an offshore wind farm, assessment of the external electrical network conditions at the wind turbine terminals must be conducted to ensure compatibility with the electrical system design, such as normal voltage and range; normal frequency, range and rate of change; voltage imbalance, etc. [53]. The electrical system design, especially the cable connection layout, plays a critical role in the energy production of a wind farm [107]. The experience shows that power cables are vulnerable to damage, being the principal cause of the failures of power supply from offshore wind farms [108]. Thus, they must be carefully designed to optimize the performance of offshore wind turbines [109].

- **Loads**

Fixed jacket offshore platforms include piles or other foundation elements that permanently anchor the platform to the ocean floor and resist both lateral and vertical loads [50]. As can be seen in **Figure 7**, the lateral and vertical loads that come from the platform structure are dead loads and live loads, and are mainly induced by the weights of the platform structure itself and the pertinent equipment and structures during the operation of the platform. When a jacket structure is repurposed as a substructure for a wind turbine, the weight borne by the substructure may be reduced [17]. Rui and Walker's study [110] of 153 global offshore platforms (mainly fixed jacket platforms, accounting for 69%) reveals that the average topside weight is 8,581 t, varying from over 200 t to more than 40,000 t. Whilst the total weights of the tower and the rotor-nacelle assembly of commonly used offshore wind turbines typically range from 234 t to 645 t [111]. However, there is a high uncertainty in the alteration of lateral loads [17]. The stress variations caused by the nacelle and hub acting at the top of the wind turbine's tower, which are point masses at the end of long arms, are significantly different from the typically low topside structure. Furthermore, the changes in masses and their distribution will cause alterations in the harmonic response of the wind turbine structure [17]. Therefore, such alteration of lateral loads must be considered for the conversion of offshore jacket structures into substructures for offshore wind turbines.

The major impact of aerodynamic loads on offshore wind turbines under combined wind-wave loading means that when converting a jacket into a wind turbine substructure, the jacket deck might have to be strengthened to allow for the movements of the wind turbine tower and the moment caused by the wind force. In addition, wave loads should be taken into account due to the susceptibility of the support structure to wave action and the extra effects of elevated water depth [54]. As Yan et al.'s study [54] was solely based on numerical simulations, scaled physical testing under combined wind-wave loading should be conducted while planning for the conversion to determine the effects of wind and wave forces more precisely.

Special attention should also be paid to seismic loads. Significant uncertainty exists regarding the effects of extreme events like earthquakes on offshore wind turbines and the appropriate design and construction methods for areas prone to such events [112]. Among existing offshore oil and gas platforms worldwide, few are in the seismic zones [113], which is an advantage. However, research on seismic responses of aged jacket platforms shows that the collapse transcendence probability of such platforms increases appreciably, by about 20%–40% compared to platforms that have not yet been in operation, which mainly results from immense corrosion [114]. Offshore oil platforms need to satisfy strength requirements, which are measured at the extreme level earthquake (ELE) and the abnormal level earthquake (ALE), to ensure no exceedence of structural damage due to earthquake shaking during the project life cycle [50]. While the response spectrum analysis method is often utilized for checking offshore oil jacket platforms at the ELE, time domain analysis is required for seismic design of offshore wind turbines and necessitates realistic or synthetic time history records [51,113]. To obtain the highest accuracy of time domain analysis, the stiffness and strength changes in the soil should be captured via dedicated constitutive models and soil-structure interaction simulation [51].

Damping is normally defined as the dissipation of the system energy to the environment and is considered an important factor that can limit the amplitude of the dynamic response and thus extend the fatigue life of the structure [115]. Among the sources of damping loads on offshore wind turbines (see **Figure 8**), aerodynamic damping on rotor blades and tower and structural damping on rotor blades and drive train [51] should be of particular concern when retrofitting offshore oil jackets to substructures of offshore wind turbines (for factors that affect the damping sources, see Lian et al. [116]), given the different modes of operation between the topside and the rotor-nacelle assembly.

6.1.3. Fatigue Design

Barros et al.'s study [3] on fixed offshore oil platforms on the Brazilian continental shelf shows that the main issue to consider when reusing offshore oil platforms for offshore wind turbines is the remaining fatigue life of the jackets to support the wind turbines. As guided in API Recommended Practice 2A-WSD, fixed offshore platforms should be designed for the appropriate loading conditions that generate the most severe impacts on the structure [50]. Then based on **Table 3** and **Table 4,** fixed offshore platforms should be designed at L-1 (the highest exposure level) and thus the minimum safety factor for the structure components is 2, i.e., the design fatigue life of each joint and member in fixed offshore platforms must not be less than twice the intended service life of the structure, which is possibly sufficient to cover the next full service life of the wind turbine structure. However, for the repurposing of offshore jackets to serve as substructures for wind turbines, the remaining fatigue life must be documented to be longer than the planned service life of the wind turbine. Of particular concern is the effect of the resonance between the rotation of the blades with the waves, leading to additional fatigue damage compared to the initial use of the structure.

In addition, the extended fatigue life of the jackets should be considered. An extended fatigue life is regarded as acceptable and within normal design criteria if the calculated fatigue life is longer than the total design life multiplied by the fatigue design factor [56]. It can be evaluated based on the results of the inspections conducted throughout the prior service life of the structure [56].

6.2. Economic Aspects

Following Baqery and Edalat's study [12] results, among the cost items that would be reduced, several are particularly noteworthy, including Platform Removal, Platform Preparation, and Mobilization and Demobilization of Derrick Barges which would only be undertaken for the topside, hence the associated costs would be reduced by half; as well as Power Cable Removal and Site Clearance which would not have to be carried out under the repurposing option, thus eliminating the relevant costs [12]. This could serve as the initial basis for the cost-benefit analysis of alternative decommissioning options for other fixed offshore jacket platforms. For example, if platform Y in this study were reused for an offshore wind turbine, about one seventh of its total decommissioning cost could be decreased compared to complete removal, by applying Baqery and Edalat's mathematical approach [12].

Current practice indicates that conversion of a fixed offshore oil platform into a fixed-bottom offshore wind turbine can make a substantial saving of installation and substructure costs, while the OPEX and the energy production should be considered for the reuse of a fixed offshore oil jacket for a fixed-bottom offshore wind turbine. To avoid escalating OPEX, particularly, proactive maintenance protocols and advanced monitoring systems, for example, with integration of Artificial Intelligence (AI) sensors should be applied [117,118]. In addition, energy-efficient maintenance practices should be considered to reduce the environmental effects of burning fuel [118]. For example, Autonomous Surface Vehicles (ASVs), which are powered by hydrogen fuel and incorporate the latest in AI and computer vision technology, can be an environmentally friendly and cost-effective option for monitoring and maintaining offshore wind turbines [119]. Advanced maintenance techniques, such as Predictive Maintenance, which is conducted based on time or power generation levels, can decrease unexpected breakdowns, enhance safety and improve the cost-efficiency of offshore wind structures [120]. For energy production, while offshore wind turbines retrofitted from offshore oil jacket platforms can be more advantageous than the turbines developed in conventional locations, a case-by-case comparison should be conducted, considering the specific site conditions.

6.3. Environmental Aspects

Research shows that for jacket platforms, RTR is the preferred option to complete the removal of the platforms [19]. This probably results from the fact that jackets' steel structures, which act as artificial hard substrate, could enhance biodiversity and ecosystem value in places where natural hard substrate used to exist [19]. However, the ecological contributions of RTR remain a topic of debate [71], which can be demonstrated through the synthesis in Section 4.3. Such contributions are also complex, varying among regions, platform sites, and species, as well as within species. In addition, the study results are influenced by the sample sizes, which are crucial for providing in-depth interpretations of data and reaching a valid conclusion [89]. Therefore, a case-by-case evaluation should be conducted to determine the ecological benefits of artificial reefs [121], which should be part of the consideration for converting offshore oil jackets into offshore wind turbine substructures. In our case study, the design of platform X shows that marine growth thickness is higher at intermediate depths, where biomass and diversity are likely to be higher [102]; however, specific evaluation still needs to be undertaken to provide precise data on the ecosystem services of the platform.

Notably, although extensive research has been conducted on RTR, there is a lack of studies on the behavior of artificial reefs over time, leading to uncertainties about artificial reefs' long-term ecological benefits [122]. Hence, ecological studies and the associated monitoring surveys should be continued during the lifetime of the offshore wind turbine.

6.4. Legal Aspects

Since 'disused offshore installation' is defined in the OSPAR Decision 98/3 as an offshore installation which is not serving its original or new legitimate purpose [20], conversion of an offshore oil jacket at the end of petroleum activities for an offshore wind turbine can be acceptable under the international legal framework. In the national legal frameworks for offshore oil and gas decommissioning of some countries such as the UK, Australia and Vietnam, that option is also admissible. If prior consultation with the competent authority is required in the UK, the conversion must demonstrate benefits, particularly equal or better environmental outcomes compared to complete removal, and comply with other requirements, including well integrity and safety in Australia and Vietnam. Then, for the offshore oil platforms investigated under this study, their jackets can be retained and retrofitted for offshore wind development following Vietnamese regulations, provided that such decommissioning alternative has proven benefits and ensures safety.

A decision-making framework that links the technical, economic, environmental and legal factors that influence the conversion of offshore oil platforms into offshore wind turbines is depicted in **Figure 9**.

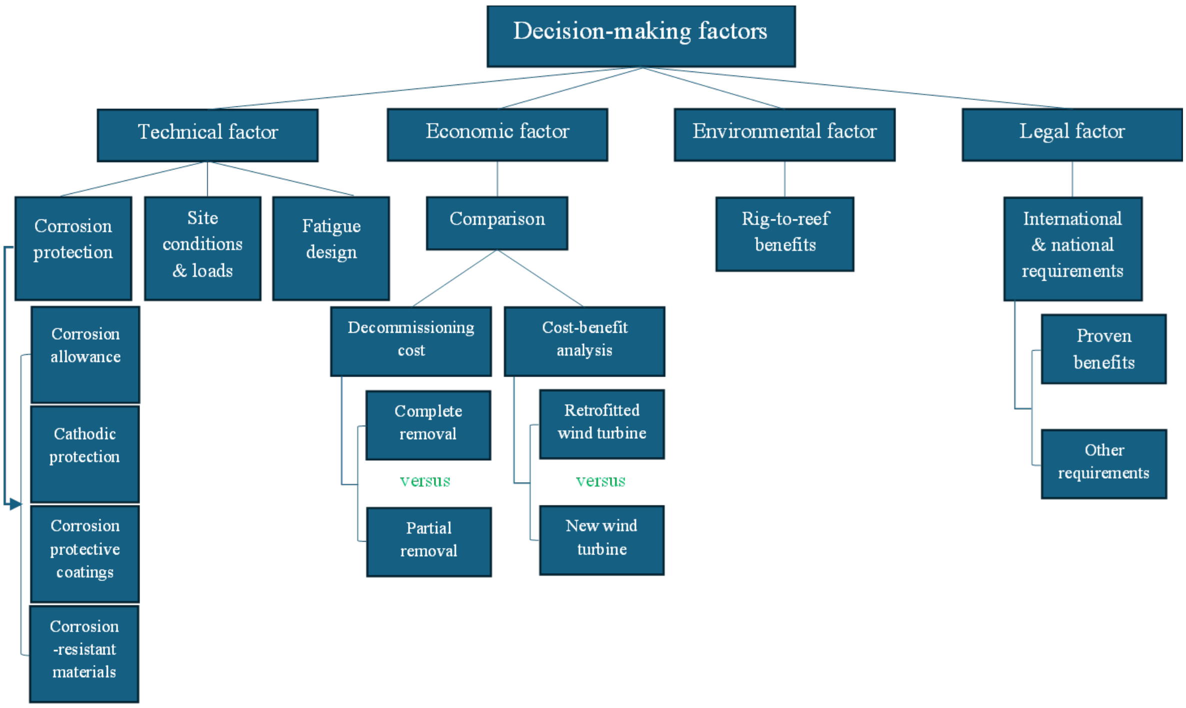

Figure 9. Decision-making framework for converting offshore oil platforms into offshore wind turbines.

7. Conclusions and Outlook

The synthesis and comparative analysis of the technical, economic, environmental and legal aspects associated with the conversion of offshore oil and gas platforms into offshore wind turbines shows that this approach is feasible and potentially beneficial to both petroleum operators and wind energy developers. For existing offshore oil and gas platforms, a case-by-case evaluation should be undertaken. For new offshore oil and gas platforms that will be established in the future, the provisions for retrofitting should be included in the initial design and fabrication of the jacket structures.

A decision-making framework for reusing offshore oil jackets as substructures of offshore wind turbines was also developed in this study. Technically, the rest-capacity of the jacket must be sufficient to serve during the design life of the wind turbine. Particular attention should be paid to corrosion protection for offshore oil jackets and offshore wind turbine structures, the site conditions and loads acting on fixed offshore platforms and offshore wind turbines, and the fatigue design. For corrosion protection, further requirements, such as those related to GACP design for fixed offshore oil and gas platforms, and the corrosion allowance for corroded components, should be set up to ensure the corrosion protection systems cover more than the service life of the jacket structure. For site conditions, electrical network conditions must be assessed to ensure they are compatible with the electrical system design, which must pay attention to the cable connection layout to optimize the energy production of the retrofitted wind turbine. For loads acting on the structures, given the change in lateral loads on the offshore jackets when retrofitted for substructures of offshore wind turbines, as well as the major influence of wind forces under combined wind-wave loading, the jacket deck may have to be reinforced. Apart from response spectrum analysis, time domain analysis should be undertaken for seismic design of offshore oil jacket platforms to prevent structural collapse during earthquake events after being retrofitted for offshore wind turbines. In relation to damping loads, aerodynamic damping on rotor blades and tower, and structural damping on rotor blades and drive train should be given close attention. Regarding the fatigue design, the design fatigue life of each joint and member in fixed offshore oil jackets that follow API Recommended Practice 2A-WSD could be adequate to cover the subsequent service life of the wind turbine; nevertheless, the remaining fatigue life of the jacket must be evaluated. Additionally, an extended fatigue life should be considered, which can be based on the results of the inspections executed during the prior service life of the jacket structure.

From an economic perspective, the lowered cost components following Baqery and Edalat's calculation method [12] could underpin the cost-benefit analysis of decommissioning options for other fixed offshore jacket platforms, for instance, the operator of platform Y in the present study could save about one seventh of the full removal cost, if the platform were converted into an offshore wind turbine. If the offshore oil jacket is retrofitted with a wind turbine by the wind operator, such an operator can benefit from significantly reduced installation and substructure costs but may face increased OPEX compared to the construction and management of a new offshore wind turbine. To optimize OPEX, proactive maintenance protocols and advanced monitoring systems, as well as energy-efficient maintenance practices, should be applied. Furthermore, a comparison of the energy production from the offshore wind turbine between the two options should be undertaken, although the reused offshore oil jacket may yield benefits from the greater water depth, which potentially results in boosted wind energy production. From the environmental viewpoint, the steel structures of offshore oil jackets could contribute to biodiversity enhancement by acting as an artificial hard substrate, with biodiversity tending to increase at intermediate depths where marine growth thickness is higher, like in the case of platform X. However, specific evaluation is necessary for judging the ecological performance of each jacket, both in the decision-making process of the conversion and during the operation of the retrofitted offshore wind turbine. Legally, in the international and some respective national contexts, repurposing an offshore oil jacket at the final stage of petroleum operations for an offshore wind turbine is allowable, which requires a permit. Under Australian and Vietnamese legal frameworks, the permit can be issued if such an alternative to complete removal can offer advantages, in particular environmental payoffs and satisfy further requirements such as well integrity and safety.

Author Contributions

Methodology, H.T.L.; Investigation, H.T.L.; Formal analysis, H.T.L. and A.H.; Data curation, H.T.L. and A.H.; Writing—original draft, H.T.L.; Writing—review and editing, H.T.L., A.H. and O.T.G.; Copyright permission acquisition, H.T.L. and O.T.G.; Analysis validation, O.T.G. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

All authors declare no conflict of interest.

AI Use Statement

The authors declare that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

Abbreviations

AI	Artificial Intelligence
ALE	Abnormal Level Earthquake
API	American Petroleum Institute
ASTM	American Society for Testing and Materials
ASV	Autonomous Surface Vehicle
CAPEX	Capital Expenditures
CP	Cathodic Protection
DNV	Det Norske Veritas
ELE	Extreme Level Earthquake
FEA	Finite Element Analysis
GACP	Galvanic Anode Cathodic Protection
ICCP	Impressed Current Cathodic Protection
LCOE	Levelized Cost of Electricity
MSL	Mean Sea Level
OPEX	Operational Expenditures
P&A	Plugging and Abandonment
PLEM	Pipeline End Manifold
PLET	Pipeline End Termination
ROV	Remotely Operated Vehicle
RTR	Rig-to-Reef
UK	United Kingdom
UKCS	UK Continental Shelf
US	United States
WHP	Wellhead Platform

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