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Repurposing decommissioned fixed jacket offshore platforms for offshore renewable energy systems: a state-of-the-art technical review

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Abstract. The global offshore oil and gas industry is facing rising decommissioning costs, which are expected to reach hundreds of billions of dollars. Decommissioning also creates significant environmental concerns. In this context, circular economy principles provide a useful direction. Repurposing decommissioned fixed steel jacket platforms for offshore renewable energy (ORE) systems can be seen as a practical alternative to full removal. This review evaluates the structural and economic feasibility of converting legacy platforms into renewable energy hubs. Findings indicate that reusing existing subsea foundations can reduce capital expenditure by 20–40% and lower the Levelised Cost of Energy. Structurally, many jackets retain substantial residual strength with utilisation ratios (UR) typically below critical thresholds after topside removal. However, transitioning to renewable applications introduces complex engineering challenges, requiring advanced Aero-Hydro-Servo-Elastic (AHSE) modelling to assess dynamic loading effects. Additionally, reliable evaluation of remaining useful life (RUL) must account for corrosion, fatigue degradation, inspection uncertainty and the as-is structural condition of ageing jackets. Beyond structural feasibility, this review highlights that repurposed offshore platforms should preferably support local offshore energy utilisation such as hydrogen or ammonia production, offshore refuelling, CO_2 sequestration, enhanced oil recovery and platform self-powering rather than relying solely on long-distance electricity export to shore. The review also emphasises the need for non-destructive testing and sensor-assisted, AI-based structural health monitoring to support safe operation of normally unattended repurposed offshore stations.

Keywords: decommissioning; offshore platforms; offshore renewable energy; repurposing; structural integrity

1. Introduction

The offshore oil and gas industry has experienced tremendous development over the past decades, resulting in the installation of thousands of offshore platforms worldwide. A significant

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number of these offshore infrastructures are approaching the end of their lifespan, particularly in the more mature offshore regions such as the North Sea, the Gulf of Mexico and parts of Southeast Asia [1]. The issue of offshore platform decommissioning has therefore become more relevant in the offshore industry, particularly among industry players and government agencies.

Traditionally, the decommissioning of offshore platforms mandated by international conventions involves the partial or complete removal of the infrastructure after production ends. The decommissioning of offshore platforms is technically challenging and costly. Global estimates suggest that cumulative offshore decommissioning liabilities could reach hundreds of billions of dollars over the coming decades, particularly in regions burdened with high concentrations of ageing infrastructure [1-2]. In some cases, the total decommissioning cost of offshore platforms can run into the billions of dollars, particularly in regions with a high density of offshore infrastructure. In addition to economic implications, decommissioning offshore platforms raises environmental concerns, including seabed disturbance, waste disposal and carbon emissions generated by prolonged heavy-lifting and marine transportation operations during decommissioning [3].

In recent years, the repurposing or reuse of decommissioned offshore platforms has gained increasing attention as a value-preserving alternative to conventional removal and disposal. This approach is closely aligned with the global energy transition and circular economy principles, as it seeks to retain the structural, logistical and spatial value of existing offshore assets rather than treating them solely as end-of-life waste [4, 9, 95]. Among the potential reuse pathways, integrating decommissioned platforms into offshore renewable energy (ORE) infrastructure is particularly promising. Repurposed platforms may reduce environmental impacts and capital costs compared with the construction of entirely new offshore support structures owing to their residual structural capacity, established seabed foundations and potential connection to offshore energy networks [5].

Among various offshore structural types, fixed steel jacket platforms represent one of the most common configurations deployed in shallow to intermediate water depths. These structures consist of highly redundant steel lattice systems supported by driven piles and were originally designed to resist extreme sea and weather conditions such as strong wave slamming, aggressive currents and hurricane-force winds [6]. Based on their strong and conservative original designs, many decommissioned jacket platforms may still have sufficient residual capacity to support alternative applications, including offshore wind turbines (OWT), wave energy devices and integrated offshore energy hubs [7].

Despite the strategic advantages of repurposing, wide commercial use of repurposed platforms is limited by methodological and regulatory gaps. Main engineering issues include time-dependent structural degradation, load compatibility between ageing substructures and new renewable energy systems, topside payload and layout limits for heavy modular equipment and subsea pipeline integrity for alternative energy carriers such as hydrogen or CO_2 transport [8]. Previous literature reviews concerning platform decommissioning have predominantly focused on the macroeconomic feasibility of reuse or the environmental impact assessments of structural removal. Few studies have approached platform conversion through a rigorous and analytical structural engineering lens. There is also a critical scarcity of integrated assessment frameworks that combine Aero-Hydro-Servo-Elastic (AHSE) dynamic load modelling with the "as-is" degraded structural condition of ageing jackets [9]. Without coupling these complex dynamic aerodynamic thrusts with accurate models of time-dependent localised corrosion and cumulative fatigue damage, predicting the true Remaining Useful Life (RUL) of a repurposed platform is highly uncertain.

Furthermore, a major regulatory gap persists because current offshore design codes lack standardised certification criteria for transitioning structures from static hydrocarbon extraction to highly dynamic renewable energy generation.

This paper presents a state-of-the-art analytical review of the repurposing of decommissioned fixed jacket offshore platforms for renewable energy systems. This review justifies its "state-of-the-art" designation by uniquely synthesising the most recent numerical case studies, advanced structural retrofitting metrics and emerging regulatory frameworks. By moving beyond the descriptive overviews found in prior literature, this paper critically analyses the methodological feasibility of integrating highly dynamic renewable energy technologies with the "as-is" degraded state of ageing jackets. Ultimately, this review aims to provide a comprehensive, up-to-date engineering baseline for the safe and standardised reuse of offshore infrastructure in future energy networks.

2. Overview of fixed jacket offshore platforms

2.1 Structural configuration of jacket platforms

Fixed jacket platforms are among the most widely used structural configurations in the oil industry, especially for water depths considered shallow or intermediate [10]. These structures have a steel lattice jacket fixed to the seabed by driven piles [11]. The jacket structure supports the topside structure, which contains drilling, production and accommodation units for oil and gas exploitation activities [12]. Due to their robust structural configuration, jacket platforms can withstand complex loading conditions caused by environmental forces [10].

The structural configuration of jacket platforms comprises three major components, which include the deck structure, jacket frame and foundation system [11] as summarised in Table 1. The deck structure, also known as the topside structure, is responsible for accommodating operational equipment and personnel requirements [10]. The jacket substructure is a braced steel structure comprising tubular members that form a lattice, which transfers loads from the topside structure to the foundation structure [11]. The foundation structure consists of open-ended steel tubular piles driven deep into the soil strata, which ensures global stability against overturning moments and sliding forces [13].

Table 1. Primary structural components of a fixed jacket platform and their engineering functions

Sub-system	Main Components	Engineering Function
Topside (Deck)	Deck legs, Main girders, Plating, Equipment skids, Helideck	▪ Houses production equipment, drilling rigs and living quarters. ▪ Provides working space.
Jacket Substructure	Tubular legs, Horizontal and diagonal braces, Nodes/Joints	▪ Acts as a rigid lattice framework to transfer topside loads to the foundation. ▪ Resists lateral marine forces.
Foundation	Driven steel tubular piles, Grout, Mud mats	▪ Anchors the platform to the seabed. ▪ Provides bearing capacity and resists overturning moments.

Jacket platforms are also influenced by various factors such as the depth of the water, environmental conditions and installation constraints [12]. Generally, the most suitable range of the jacket platforms is found in the range of 20 m to 150 m in the offshore environment. Within this range, the structural efficiency and the installation feasibility of the jacket platforms are the reasons why this type of offshore structure is the most preferred over the others [10]. Indeed, there are thousands of jacket platforms installed worldwide, especially in the offshore environment in the North Sea, the Gulf of Mexico and Southeast Asia [13].

From a structural engineering perspective, jacket platforms are designed to maximise stiffness and ultimate strength while using minimal materials [10]. The jacket relies on an axial push-pull load-transfer mechanism within its space frame rather than on global bending [14]. The tubular members are sized based on operational and environmental loads. The chords of primary loading members such as jacket columns and driven piles have outer diameters (OD) ranging from 1.37 m to 1.52 m for mid-depth platforms. The bracing members are smaller to allow for weight optimisation and are tapered from 61 cm at the bottom bays to 45 cm at higher elevations. The average wall thickness is about 20 mm, but the minimum pile wall thickness required for resistance against driving forces during installation is based on API guidelines [15]

$$t = 6.35 + \frac{D}{100} \tag{1}$$

where t is the minimum wall thickness in mm and D is the pile diameter in mm.

Locally, there are significant stresses due to the transfer of loads in tubular joints such as K, T and Y joints, where braces are attached to the main chords of the platform. Modern approaches to structural assessment now use Hot Spot Stress (HSS) and Stress Concentration Factors (SCFs) instead of nominal beam stresses, as proposed in Iqbal et al. [16]. In a corrosive seawater environment with dynamic wave and wind loads, localised fatigue damage in tubular joints is a dominant design constraint for offshore platforms. The dynamic stress range ($\Delta\sigma_{cor}$) can be assessed using a fatigue degradation equation [17]

$$\Delta\sigma_{cor} = \bar{a}_1^{1/m_1} N_{LCF}^{c} N^{\left(-c-\frac{1}{m_1}\right)} \tag{2}$$

where N is the predicted number of cycles to failure, N_{LCF} is the low-cycle fatigue intersection point, $\bar{a}_1$ and m_1 are standard S-N curve parameters and c is the environmental degradation exponent.

The extensive deployment of jacket platforms in the offshore environment over the past several decades has generated a massive global inventory of ageing offshore infrastructure approaching or exceeding the end of its useful life [18]. Although these platforms were originally developed for hydrocarbon production, their residual structural capacity, foundation systems and offshore accessibility create opportunities for alternative post-production uses [19]. This has encouraged researchers and industry stakeholders to examine the feasibility of repurposing existing jacket platforms for sustainable offshore applications, particularly as support structures or service hubs for offshore renewable energy systems [9].

2.2 Design characteristics and operational life

Offshore jacket platforms are designed for an operational life of around 20 to 30 years, depending on the environmental factors and operational requirements at the site where the jacket is

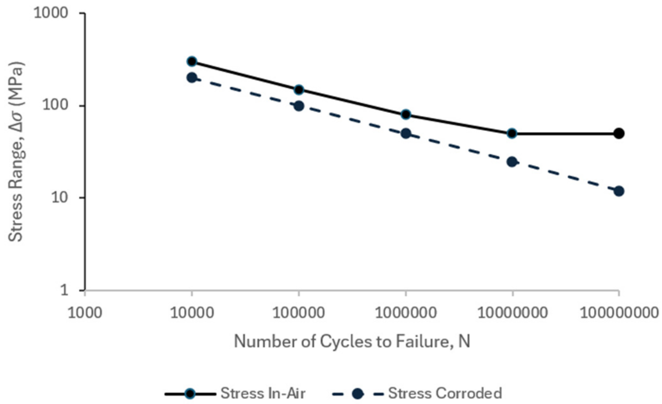

Figure 1. Schematic representation of standard S-N curves for offshore tubular joints, illustrating the elimination of the Constant Amplitude Fatigue Limit (CAFL) and overall life reduction in freely corroding environments (Conceptual schematic redrawn by the authors based on DNV [21])

to be placed [7]. During the preliminary and detailed design stage, several factors are considered, including extreme wave heights, wind velocities, ocean currents and geotechnical seabed profiles.

All these factors are crucial for determining the Ultimate Limit State (ULS) of the structural configuration, sizes of the members and foundation of the jacket platforms [20]. The environmental load safety factors typically range from 1.35 to 1.50, depending on the design code [6]. The key design limit states and degradation mechanisms governing these decisions are summarised in Table 2. To ensure the structural reliability of offshore platforms during their operational life, jacket platforms are designed in accordance with standard engineering practices and codes such as ISO 19902. At the design stage, detailed numerical modelling and analysis are conducted to determine the response of the offshore platforms under different loading conditions [10].

Among the various design criteria, the Fatigue Limit State (FLS) is particularly critical while designing offshore steel structures. Jacket platforms experience constant low-amplitude cyclic loading driven by sea waves, wind fluctuations and rotating machinery. The fatigue capacity of a structural member is determined using empirical S-N curves, which are based on a relationship between the stress range ($\Delta\sigma$) and the number of cycles to failure (N). As shown in Fig. 1, the slope and position of the S-N curve are significantly influenced by environmental conditions. Joints in a freely corroding seawater environment are found to lose 50% to 70% of the fatigue life with a life reduction factor of about 2 to 3 and lose their Constant Amplitude Fatigue Limit (CAFL) in comparison to those in air or under Cathodic Protection, according to DNV [21]. The standard form of the empirical relationship for these curves is

$$\log N = \log \bar{a} - m \log \Delta\sigma \tag{3}$$

where $\bar{a}$ and m are empirical material constants derived from fatigue testing. Fatigue cracks develop in the structure and particularly at the welded tubular joints where Stress Concentration Factors (SCFs) are highest over a period [22]. For typical offshore tubular configurations such as T, Y and K joints, SCF values generally range from 2.0 to 8.0, though they can exceed 10.0 in highly complex, multi-planar nodes [22]. Fatigue analysis is an integral part of the design of offshore jacket structures [23].

Table 2. Key Design Limit States, Degradation Mechanisms and Remaining Useful Life Assessment for Fixed Jacket Platforms

Degradation Factor	Engineering Definition	Primary Drivers & Environmental Loads	Quantitative Metrics and Design Parameters	Mitigation and Assessment Strategies	Reference
Ultimate Limit State (ULS)	Maximum load-carrying capacity to prevent structural collapse or yielding.	Extreme 50 or 100-year return period storms, hurricane winds, max wave heights and dead weights.	Environmental load safety factors typically range from 1.35 to 1.50, depending on the design code.	Robust member sizing, high-strength steel utilization and redundant structural bracing.	[6, 26]
Fatigue Limit State (FLS)	Prevention of failure under repeated, cyclic dynamic loads (high-cycle, low-amplitude).	Daily wave action, wind-induced vibrations, operational machinery dynamics.	Typical Stress Concentration Factors (SCFs) range from 2.0 to 8.0. Allowable damage ratio (D) is usually $\leq 0.1 - 0.50$.	Smooth weld profiling, minimizing SCFs at tubular nodes.	[21, 23]
Material Degradation (Corrosion)	Loss of structural steel wall thickness leading to reduced yield strength.	Seawater salinity, dissolved oxygen, splash zone wet/dry cycling, microbial activity.	Unprotected splash zone corrosion rates are **0.3 to 0.8 mm/year**. Submerged zones: **0.1 to 0.2 mm/year**. Free corrosion reduces fatigue life by **50% to 70%**.	Cathodic Protection (CP) via sacrificial anodes, marine coatings and corrosion allowances.	[7, 21, 24]
Remaining Useful Life (RUL)	The estimated additional safe operational time beyond the original design life.	Actual encountered metocean data and design extremes, accumulated fatigue damage.	RUL is viable if the updated $D < 1.0$ using hindcast metocean data. Often yields 10 to 20+ extra years of capacity.	Structural Health Monitoring (SHM), Non-Destructive Testing (NDT), finite element reanalysis.	[20, 25]

Cumulative fatigue damage is then quantified using the Palmgren-Miner linear damage hypothesis

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} \tag{4}$$

where D is the cumulative damage ratio, n_i is the number of applied load cycles at the stress range i and N_i is the allowable number of cycles at that stress range from the corresponding S-N curve. While theoretical failure occurs at $D = 1$, design codes frequently enforce stricter thresholds like allowable $D \leq 0.1\ to\ 0.5$ for uninspectable or highly critical joints [21].

In addition to fatigue effects, corrosion presents a relentless threat to structural integrity while designing offshore steel structures. The marine environment is highly corrosive due to the presence of high salinity, dissolved oxygen and biological organisms [7]. Without intervention, localized and uniform corrosion would progressively reduce the wall thickness and load-bearing capacity of the steel members, particularly in the highly vulnerable "splash zone." Offshore platforms are provided with corrosion protection measures, combining sacrificial wall thickness allowances, high-performance protective coatings and Cathodic Protection (CP) systems in the submerged zones to avoid the effects of corrosion [24]. Despite all these protective mechanisms, structural degradation may still be experienced over long periods of service. As offshore platforms age, the effects of fatigue, corrosion and environmental factors may accumulate and impact the structural reliability of the platforms [20]. Eventually, many offshore platforms may reach a stage where continued service becomes economically or technically unfeasible, hence the need for decommissioning [25].

However, it should be noted that even after the termination of operations, many jacket offshore platforms may still have considerable structural capacity [7]. Because conservative initial designs were over-designed with high safety factors and actual metocean conditions are often less severe than the 100-year extreme conditions used in the original design, many older jackets still have significant Remaining Useful Life (RUL). This situation has made it possible to consider alternative uses for these platforms rather than decommissioning them. In recent years, the life extension of offshore platforms through repurposing has received increasing attention. This approach can support cost reduction and sustainable offshore infrastructure development.

2.3 Structural condition of ageing offshore platforms

As offshore platforms reach the end of their design service life, structural degradation becomes an important factor in assessing whether life extension is possible [23]. These platforms are exposed to severe marine conditions for many years. This exposure can lead to various forms of structural degradation. For offshore jacket platforms, the main degradation modes include corrosion, fatigue failure and accidental or environmental damage [27].

Corrosion is one of the major degradation modes of offshore steel structures [28]. Offshore platforms are constantly exposed to highly oxygenated seawater and microbial activity leads to both uniform wall thickness and localised pitting corrosion over time. As a result, the ultimate buckling and yielding capacity of the members can be greatly reduced. This problem is most serious in the splash zone. In this zone, repeated wet and dry conditions accelerate the electrochemical breakdown of steel [7]. Offshore platforms are usually designed with corrosion protection measures such as protective coatings and Cathodic Protection (CP) systems. However, these measures may become less effective during long-term service. This can happen because of anode depletion and coating degradation, especially when proper maintenance and inspection are not carried out [29].

Fatigue damage is also a major concern for ageing offshore platforms [30]. Ocean waves create repeated hydrodynamic loading with high cycles and low amplitudes. This loading can cause small cracks to form in the joints and connections of the platform. If these cracks are not found and controlled through maintenance, they can grow and lead to structural failure. Fatigue damage often occurs in areas with high stress concentration such as tubular joints and brace connections within the jacket framework [13]. Apart from corrosion and fatigue, offshore platforms may experience accidental damage due to ship collisions, dropping of objects from topside lifting operations and extreme environmental conditions [27]. Such discrete events introduce dents, global bowing of braces or pile exposure, immediately degrading the ultimate strength and redundancy of the spatial framework [6].

Given the rate of these degradation mechanisms and the extremity of future environmental conditions are inherently uncertain, current life extension assessments must be based on a probabilistic reliability perspective rather than relying solely on deterministic safety factors [31]. The structural condition of an ageing offshore platform is quantitatively evaluated in terms of the probability of failure (P_f) and its associated reliability index (β). According to basic structural reliability theory, the reliability index is mathematically expressed as [32]

$$\beta = -\Phi^{-1}(P_f) \quad (5)$$

where Φ^{-1} is the inverse standard normal cumulative distribution function.

For a newly constructed offshore structure, the initial value of β is normally higher, such as $\beta \geq 3.0$ which means that P_f is very low. However, as corrosion continues to reduce the cross-section of the structure and fatigue cracks grow, the structural resistance distribution shifts downward and widens due to increased uncertainty. This leads to a decrease in β as the probability of failure while P_f increases over time [33].

Operators in offshore environments rely on Risk-Based Inspection (RBI) techniques based on international standard protocols to manage declining reliability and maintain structural integrity [6], [34]. Instead of inspecting all components equally, probabilistic calculations are made to obtain time-dependent P_f values for individual joints and then correlate these values with the consequences of failure [35]. This enables engineers to efficiently optimise inspection activities towards specific tubular nodes in which the reliability index is expected to fall below a certain acceptable threshold (β_{target}) as per design codes.

Ultimately, the technical feasibility of the repurposing process is determined by demonstrating that the reliability index of the ageing infrastructure is still above β_{target} or that the index can be improved through retrofitting [36]. Risk-based inspection (RBI) techniques and structural health monitoring can help control the probability of failure. With these methods, strong jacket structures can be repurposed to support renewable energy devices. This approach can extend the service life of the infrastructure. It can also delay the environmental and financial burdens linked to decommissioning [37].

3. Decommissioning of offshore platforms

3.1 Conventional decommissioning methods

Decommissioning is the final and highly complex stage in the life cycle of an offshore oil and gas platform. This process includes the removal and disposal of platform components. Many offshore platforms worldwide are now reaching the end of their service life. Hence, decommissioning has become a major concern for the offshore energy sector [38]. The typical design life of offshore oil and gas platforms is 20 to 30 years. As a result, thousands of offshore structures now require safe and strictly regulated disposal [39]. Decommissioning methods are usually shaped by regulatory requirements, environmental concerns and economic limits [3]. These approaches differ across countries and regions. They are generally divided into three main categories: complete removal, partial removal and reefing.

Complete removal is the conventional process where all platform components are dismantled and transported to shore for disposal or recycling. This approach is the default requirement under OSPAR Decision 98/3 in the North Sea. The decision requires the full removal of most offshore steel structures. This involves the dismantling of the topside structures, well plugging and abandonment (P&A), the lifting of the topside modules using Heavy Lift Vessels (HLVs) and the cutting of jacket foundation piles several meters below the mudline using abrasive water jets or internal mechanical cutters [25, 40].

Partial removal is different from complete removal. This method removes only part of the structure. In most cases, the upper jacket is removed to reduce surface hazards. The lower sections

Table 3. Engineering Comparison of Conventional Decommissioning Strategies

Approaches	Relative Cost Impact	Relative CO_2 Emissions	Structural Reuse Potential (Energy/Industry)
Complete Removal	Baseline (100%) [44]	Highest, extensive HLV use, transport and onshore smelting [43]	**Very Low**: Scrapped and melted for raw material recycling [45]
Partial Removal	Medium (~50–80%) [44]	Medium: Reduced HLV time and transport [44]	**Low**: Topside destroyed, lower jacket remains in situ but inaccessible [45]
Reefing (Toppled)	Lowest (~20–50%) [44]	Lowest: Minimal lifting and marine logistics required [44]	**None**: Structure fully submerged and permanently abandoned for habitat

Note: Relative costs and emissions are approximated against the baseline of Complete Removal

are kept in place, especially when they have already become part of the marine environment. This strategy is sometimes employed to reduce the cost and complexity of decommissioning, especially for large offshore structures built on the seabed in deeper waters [3]. However, the partial removal strategy must comply with the regulations to avoid any potential hazards to navigation and the seabed. Studies have shown that even partial removal can retain up to 80% of the biomass of marine species, as most of the marine life resides in the deeper, more complex sections of the jacket [41].

Another strategy used for decommissioning offshore structures is to topple them onto the seabed to serve as artificial reefs. Reefing is most common in the Gulf of Mexico through the Rigs-to-Reefs program, which involves converting decommissioned platforms into artificial reefs. Over 500 reefed structures exist in the Gulf of Mexico, making it one of the most successful ecological reuse initiatives worldwide [42]. This method has been utilised to decommission some offshore structures to promote biodiversity and reduce decommissioning costs. Under this approach, structures are left on the seabed or are moved there after hazardous and operational equipment have been removed.

Although these conventional measures offer practical solutions for evaluating ageing offshore infrastructure, there is a tendency for such measures to be linked to major financial and environmental challenges. According to Table 3, there is a significant trade-off between environmental impact, cost and preservation of assets. The full removal option is used as the basis for the maximum cost and the associated maximum CO_2 emissions due to the extensive use of Heavy Lift Vessels (HLVs) and the onshore smelting [43]. Conversely, while the partial removal and reefing options significantly reduce the associated carbon emissions and capital expenditure (CAPEX) by minimising the logistics required in the marine environment [44], there is no significant option for the reuse of the structure in the energy sector as the structure is either partially destroyed or abandoned completely to the marine environment [45].

Due to the complexity of offshore operations, the costs of decommissioning the infrastructure can be extremely high. In fact, the cost of decommissioning the offshore oil and gas infrastructure is estimated to be in the hundreds of billions of dollars over the coming decades. This large economic burden and the carbon footprint from demolition have increased the need to find other strategies. These strategies should retain the value of existing offshore platforms such as platform repurposing.

3.2 Environmental and economic implications

The economic and environmental effects of offshore platforms are important in offshore decommissioning decisions. From an economic view, decommissioning is a major financial burden for operators and government stakeholders. It is often one of the largest costs in the life cycle of an offshore asset. Global decommissioning costs are expected to rise far above current levels. These costs are estimated to exceed USD 42 billion in the Asia-Pacific region alone and more than USD 100 billion globally in the coming decade [1]. This increase is linked to the large number of ageing offshore installations. The main costs come from plugging and abandonment (P&A) operations, heavy-lift vessel use, subsea cutting, waste processing and onshore dismantling.

Environmental issues are also important in offshore decommissioning decisions. Decommissioning activities can disturb seabed sediments and cause seabed scarring. Large marine vessels can also release gases and other pollutants during these operations. Accidental hydrocarbon leaks can occur and waste from decommissioning can also harm marine ecosystems if not properly managed. The removal of driven piles and subsea infrastructure can cause serious disturbance to benthic habitats, leading to the resuspension of potentially contaminated seabed sediments. Furthermore, the demolition and onshore disposal process generates large amounts of industrial waste, including corroded structural steel, marine pipelines and naturally occurring radioactive materials (NORM). The heavy use of marine vessels during decommissioning also adds to the overall carbon footprint [46].

Marchetti et al. [47] note that lifecycle assessment (LCA) is an effective methodology in quantifying environmental impacts and provides evidence-based comparisons among different decommissioning options. Recent environmental studies have shown that the removal of offshore platforms creates substantial carbon emissions because a platform apart and recycling the steel on land [48-49]. For example, a recent site-specific LCA of the Clara platform in the Mediterranean Sea demonstrates the severe operational footprint of conventional decommissioning. The study found that the significant marine logistics and cutting operations required for the full removal of the structure resulted in 14300 kg of CO_2 equivalent emissions. By contrast, the partial removal approach reduces operational emissions by almost 78%, with emissions reduced to only 3090 kg of CO_2 equivalent [47]. Although the full removal option can be seen as providing offsets in the form of carbon emissions reduction through the recycling of the structure’s steel material in the process of repurposing the structure in place, it is important to note that the repurposing option completely avoids the exorbitant energy expenditure required in the process of full removal in the first place [50]. For this reason, regulatory authorities increasingly require operators to demonstrate not just compliance but also environmental responsibility through emissions reporting, biodiversity protection measures and the adoption of green technologies.

Despite these challenges, some studies suggest that keeping these structures may support environmental protection. This is because jacket platforms can provide habitats for different marine species as it has potential to act as artificial reefs. Therefore, complete removal of an offshore platform may disturb the ecosystem that has developed around it during its service life. Due to the high costs and environmental impacts of traditional decommissioning, different strategies for managing ageing offshore infrastructure have received more attention in recent years. The reuse of these large existing facilities for other purposes has become more attractive, especially for offshore renewable energy (ORE) production. This method not only avoids the economic burden linked to full removal but also protects existing marine ecosystems, providing a sustainable transition route for ageing offshore structures.

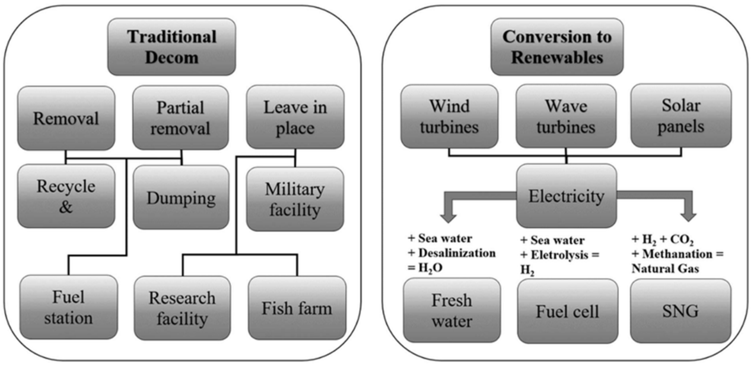

Figure 2: Strategic Comparison between Traditional Decommissioning and Conversion to Renewable Energy Hubs, reproduced from Braga et al. [57] under the terms of the Creative Commons Attribution (CC BY 4.0) license

3.3 Alternative strategies: repurposing and reuse

Repurposing offshore platforms means using existing offshore infrastructure for new purposes after hydrocarbon production ends [51]. Instead of decommissioning these offshore platforms, operators are now exploring new uses for repurposing them. These uses include renewable energy generation, carbon capture and storage (CCS), deep-sea aquaculture and marine research hubs [52]. For example, Bahadur [53] proposes using decommissioned platforms to capture CO_2 from seawater and form stable seafloor hydrates by eliminating costly CO_2 transport. Likewise, Vreeburg & Garcia-Navarro [54] demonstrate that many North Sea gas platforms have enough space to accommodate PEM electrolysers for green hydrogen production at a feasible scale. In short, repurposing can thus transform legacy structures into blue economy assets by reducing the environmental impact of decommissioning.

In this circular-economy paradigm, repurposed platforms serve as energy islands that integrate offshore hubs, combining multiple renewable sources [55]. As illustrated in Fig. 2, such platforms may accommodate offshore wind turbines (OWT), wave energy converters (WEC), power conversion systems and auxiliary offshore utility systems. However, the value of these hubs should not be evaluated solely from the perspective of exporting electricity to shore. Many decommissioned oil and gas jackets are isolated and located far from onshore demand centres, making long-distance subsea power transmission costly and technically challenging due to cable installation cost, transmission losses and project complexity [61-62]. Therefore, a local-first utilisation strategy is often more practical, whereby renewable power generated on or near the repurposed platform is consumed offshore by co-located systems.

Under this local-first concept, the generated offshore power can support desalination, hydrogen production, ammonia or synthetic fuel production, CO_2 injection into depleted reservoirs, enhanced oil recovery (EOR), offshore refuelling operations and platform self-powering [53-54, 56, 61-63]. Electricity export to shore may still be considered but it should be treated as a secondary option and justified through site-specific cable distance, power demand, transmission loss and techno-economic assessment. In this sense, a repurposed jacket should not be viewed merely as a renewable energy foundation, but as a synergistic offshore energy hub that couples power generation with local energy conversion, storage, utilisation and carbon-management functions.

The system-level performance of such a hub can be represented using a basic energy balance, in which total generation is balanced against local demand and system losses

$$\sum_i P_{\text{gen},i} = \sum_j P_{\text{load},j} + P_{\text{loss}} \tag{6}$$

where generators (wind, wave and solar) feed loads (desalination pumps, electrolysers, base platform systems) and account for conversion or storage losses. Such examples illustrate the need for detailed multi-source modelling. Notably, the energy conversion efficiency is low [58]. The round-trip efficiency from wind to electricity and finally to electrolytic hydrogen is only on the order of 30–50%, limited by electrolysis (60% to 75%), compression or storage (80% to 90%) and fuel cell reconversion (50% to 60%) [59-60]. This underscores the importance of including storage losses and conversion inefficiencies in design. For example, if wind turbines are 40% efficient at converting wind power into electricity, the electrolyser is 70% efficient and the hydrogen fuel cells are 50% efficient, the overall round-trip efficiency of the process is approximately 0.40×0.70×0.50 ≈ 14%. Kojima [58] notes that the round-trip efficiency of wind power to hydrogen is between 28% to 52%, corresponding to modern low-voltage electrolysis.

Current literature lacks a comprehensive system model for these hybrid platforms. In a recent paper, Wiegner et al. [64] note that most of the literature addresses components of offshore energy platforms such as turbine design and cable technology and suggest a holistic and integrated system model of offshore energy platforms. EnergyPLAN, HOMER, MATLAB/Simulink, TRNSYS and P-Graph are some of the modelling tools used for offshore energy platforms [65]. Generally, offshore energy platforms are modelled using power flows and energy balance equations to compute system performance and cost. For example, EnergyPLAN uses a linearised sector coupling and load matching, whereas HOMER applies a mixed-integer optimisation of component sizes under demand constraints [65].

However, the successful implementation of repurposing the existing offshore platform depends on addressing structural integrity, safety and compliance [4]. The feasibility in this regard is to be assessed by conducting thorough Aero-Hydro-Servo-Elastic (AHSE) coupling analyses to validate the jacket's suitability for withstanding the specific dynamic load profiles of wind rotors, which differ markedly from the quasi-static loads in the original oil and gas operations [66]. In addition, site-specific analysis may be required to validate the Residual Strength Ratio (RSR) and retrofitting may be necessary in the splash zone to accommodate the new topside loads and to ensure a secondary life of 20 to 25 years [7].

As the global energy sector shifts toward developing low-carbon energy systems, repurposing offshore platforms for renewable energy applications is expected to play a vital role in the sustainable management of offshore infrastructure. There may be technical and regulatory challenges. Integrating legacy O&G platforms into renewable energy systems can provide a practical way to reduce the environmental and financial burdens of offshore decommissioning.

4. Offshore renewable energy integration concepts

Global progress in low-carbon energy systems has supported the growth of offshore renewable energy technologies in recent decades. Growing concerns over climate change, energy security and depletion of fossil fuel reserves have prompted governments and energy stakeholders to invest heavily in renewable energy infrastructure. Offshore sites provide a favourable environment for

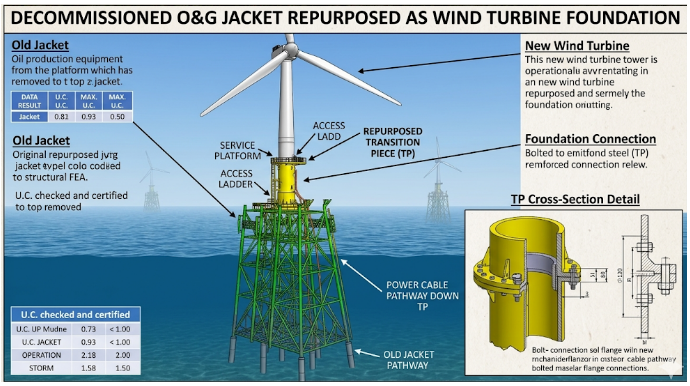

Figure 3. Technical schematic of a repurposed O&G jacket foundation showing the Transition Piece (TP) interface and FEA-verified structural integrity (U.C.) results. Schematic created by the authors based on offshore wind repurposing concepts and structural assessment criteria reported in [4, 9, 23, 86]

renewable energy technology development as wind speeds are stronger and more constant and there are fewer geographical constraints.

In recent years, a considerable number of offshore oil and gas platforms have reached the end of their operational life. This provides a unique opportunity to incorporate renewable energy systems into existing infrastructure. Rather than removing existing ageing offshore platforms, it is proposed that these could be repurposed as renewable energy hubs, thereby significantly reducing installation costs and environmental impacts associated with building new offshore infrastructure. Specifically, fixed jacket platforms provide a favourable structure in terms of foundation and access, making them suitable candidates for offshore renewable energy technology installation.

Various forms of offshore renewable energy have been considered in terms of repurposing such as offshore wind energy, wave and tidal energy systems and hydrogen production systems. All these systems have different technical demands and challenges that should be considered when repurposing existing offshore structures.

4.1 Offshore wind energy

Among the diverse portfolio of offshore renewable energy sources, offshore wind energy is the most developed and mature one at the moment [67]. Over the past decade, offshore wind farms have seen rapid growth, especially in the North Sea, East Asia and the United States. Global offshore wind capacity reached approximately 83 GW by the end of 2024 and annual offshore wind installations are projected to increase from around 8 GW in 2024 to 34 GW by 2030 [2]. Offshore wind turbines have several advantages over onshore wind systems. Offshore sites usually have higher and more stable wind speeds, which might lead to higher capacity factors and superior energy yields.

Offshore wind turbines (OWT) are supported by different foundation types like monopiles, jackets, gravity bases and floating structures. The selection depends on water depth and geotechnical conditions. Monopiles are commonly used in shallow water. Jacket structures are often used in intermediate water depths (30 m to 60 m) due to the high structural stiffness and can resist dynamic environmental loads [5]. OWT jacket structures are structurally similar to fixed jacket platforms used in the offshore oil and gas industry. This similarity creates an important

Table 4. Comparative Analysis of Design Requirements: Oil & Gas vs. Offshore Wind Repurposing

Design Parameter	Oil and Gas Platform	Repurposed Offshore Wind (OWT)	Engineering Implication
Primary Loading	Gravity-dominant (Topside weight) and wave-dominant.	Thrust-dominant (Rotor aerodynamic thrust of 1–2.0 MN) and dynamic-dominant.	Shift in critical stress points from legs to bracing and transition joints.
Dynamic Response	Stiff structures, the natural frequency is usually high (>0.5 Hz).	Requires "soft-stiff" design to avoid 1P (0.1–0.2 Hz) and 3P (0.3–0.6 Hz) frequency bands.	Risk of resonance and requires precise modal analysis and evaluation of Dynamic Amplification Factors (DAF).
Fatigue Life	Designed for 20-30 years of wave cycling.	Subject to high-cycle aerodynamic fatigue (rotor motion).	The remaining fatigue life (RFL) assessment is mandatory for life extension.
Foundation Load	Compression-heavy piling.	High overturning moments (10-30 MNm) and cyclic tension or compression.	Piling capacity and soil-pile skin friction must be re-validated.
Topside Interface	Integrated deck for production equipment.	Requires a Transition Piece (TP) for tower flange connection.	Structural modification of the jacket "splash zone" or top bay.

opportunity to reuse decommissioned offshore platforms as foundations for wind energy systems [4, 9]. Fig. 3 shows this concept through a technical schematic. The figure includes a specialised Transition Piece (TP) which connects the legacy jacket to the wind turbine tower. The structural data also support the feasibility of this approach. The Unity Check (U.C.) values for both “Operation” and “Storm” load cases remain below 1.0, which stays within safe limits.

The repurposing and reuse of existing jacket structures for offshore wind equipment offer several advantages. First, the existing foundation can reduce costs by eliminating the need for new subsea fabrication and piling. Secondly, the existing topside infrastructure can support the installation and operation of wind equipment. Thirdly, the reuse of steel in-situ follows circular economy principles. It can also reduce the carbon footprint and seabed disturbance linked to full decommissioning and new construction [19].

However, the structural integration of wind equipment into existing offshore structures requires structural evaluation. Offshore wind turbine technology faces enormous dynamic forces due to aerodynamic forces and rotor operations. In this regard, one key measurement for assessing the impact on the jacket foundation structure is the Dynamic Amplification Factor (DAF), which quantifies how these dynamic operational loads amplify the underlying static structural stresses. Jacket-type systems retrofitted with turbines can use DAFs from coupled AHSE simulations, while the typical DAFs range is 1.2 to 2.0, depending on modal proximity, damping and rotor inertia [68]. Additionally, the impact of high-frequency cyclic loading generated by rotor rotations (1P) at 0.1 Hz to 0.2 Hz and blade passage frequencies (3P) at 0.3 Hz to 0.6 Hz needs to be considered [69]. It is important to ensure that no resonance conditions occur when the cyclic loading frequency coincides with the jacket's natural frequencies. Thus, engineers strive to achieve a "soft-stiff" design, ensuring the repurposed platform's fundamental natural frequency falls safely between the 1P and 3P bands, which the target ranges to avoid are 0.2 Hz to 0.5 Hz for the first few excited modes. This is a radical change compared to the classic design of oil and gas platforms, which are highly stiff structures with natural frequencies usually well above 0.5 Hz.

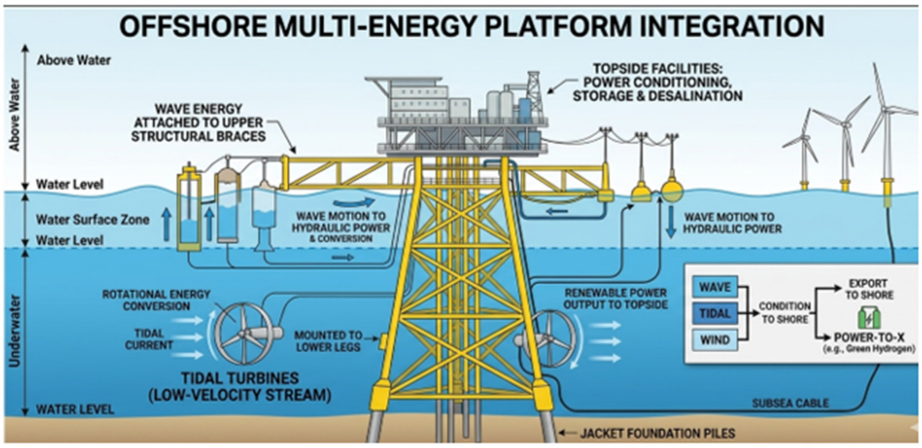

Figure 4. Technical schematic of a fixed jacket platform repurposed for multi-energy integration, showing the integration of wave energy converters, tidal turbines, offshore wind power and Power-to-X functions into a sustainable marine renewable energy hub. Schematic created by the authors based on hybrid offshore renewable energy integration concepts reported in [72-77]

A comparative analysis of these shifting design requirements and their engineering implications is presented in Table 4. The turbine thrust and moment envelopes are used to design reinforcement requirements and pile foundation checks. In the case of the current turbine capacity in the range of 5 MW to 6 MW, the maximum thrust at rated wind speed will range from 1.0 to 2.0 MN [70]. While gusting storm wind conditions will have even higher thrust values, resulting in bending torques ranging between 10 MN·m and 30 MN·m at the tower base.

Despite these challenges, various conceptual studies and pilot projects have shown the possibility of integrating offshore wind energy systems with existing offshore platforms [71]. As the global energy transition accelerates, repurposing these existing platforms could provide a strategic and cost-effective pathway for renewable energy systems.

4.2 Wave and tidal energy systems

Apart from the wind energy available at sea, the marine environment offers vast potential for Marine Hydrokinetic (MHK) power generation, primarily through wave and tidal energy systems [37]. These energy resources have gained popularity as potential contributors to the global renewable energy mix. These energy resources are referred to as marine energy systems as they exploit the kinetic and potential energy available in the ocean. Even though wave energy technology is less advanced compared to tidal energy technology, which in turn is less advanced compared to wind energy technology, these energy resources have great potential to contribute to the global renewable energy mix in the future [72]. As shown in Fig. 4, the Offshore Multi-Energy Platform Integration concept shows the capability and potential for existing fixed jacket structures to be employed as a hub, integrating both wave and tidal technologies with existing wind turbines. As shown in the above schematic, it is quite evident that the wave energy converter (WEC) machines can be mounted on top of the upper bracing members, where the energy from the waves is employed to convert the hydraulic power, and tidal turbines are mounted at the lower legs to utilise rotational energy from tidal currents and low-velocity subsea currents [73].

Wave energy converters are usually deployed in areas with sufficient wave height and wave period [74]. However, deploying and maintaining wave energy converters at sea is a technically and financially challenging operation. Therefore, the deployment of established structures such as decommissioned oil and gas platforms has emerged as a potential option for wave energy converters [72]. Tidal energy offers a new potential option for the exploitation of marine renewable energy with the predictable tidal currents generated by the gravitational attraction among the Earth, the moon and the sun. Unlike wind and wave currents, tidal currents are predictable and have a regular pattern, making them an attractive option for exploiting their electricity-generating potential. Combining these systems on a single decommissioned oil and gas platform maximises the utility of existing infrastructure and creates highly efficient, multi-source renewable energy networks [75].

The wave energy and tidal current resources may both be installed on the same fixed jacket platform to create an adaptive multi-energy cluster, but sound engineering design will require proper hydrodynamic and coupled systems modelling. The wave energy power density is typically estimated from spectral parameters using

$$P_{wave} = \frac{\rho g^2}{64\pi} H_s^2 T_e \tag{7}$$

where ρ is seawater density, g is gravity, H_s is the significant wave height and T_e is the energy period. While the device output is represented as

$$P_{WEC}(t) = \eta_{PTO} P_{hyd}(t) \tag{8}$$

where P_{hyd} is the instantaneous hydraulic or mechanical capture while η_{PTO} is the power-take-off efficiency. Tidal turbines are commonly modelled with the actuator-disk relation

$$P_{turbine} = \frac{1}{2}\rho A C_p U^3 \tag{9}$$

with A is the rotor swept area, C_p is the power coefficient and U is the undisturbed current speed.

Despite these promising hybrid configurations, large-scale integration requires rigorous hydrodynamic modelling. The physical addition of WECs and tidal turbines fundamentally alters the wave kinematics and current flow fields around the platform. Engineers apply the Morison equation to quantify the augmented dynamic loads exerted on the jacket framework. The total hydrodynamic force per unit length acting on a vertical cylindrical member is calculated as the sum of the drag force and the inertia force

$$F(t) = \frac{1}{2}\rho C_D D|u(t)|u(t) + \rho C_M V\ddot{u}(t) \tag{10}$$

where C_D is the drag coefficient, C_M is the inertia coefficient, ρ represents the seawater density, D is the member diameter, V is the displaced volume and $u(t)$ is the water particle velocity.

These equations form the basis for coupled Aero-Hydro-Servo-Elastic (AHSE) or fluid–structure interaction (FSI) simulations, which are essential to evaluate dynamic amplification, fatigue life and the Residual Strength Ratio (RSR) before retrofit [76-77]. However, with the continued technological advancements and the increasing need for alternative energy systems, the marine energy systems will become crucial components of the future energy networks. The repurposing of the decommissioned platforms can be a useful means of promoting the development of wave and tidal energy technologies while minimising the environmental and economic impacts of constructing new platforms.

4.3 Offshore hydrogen production

In addition to direct electrical transmission, the offshore renewable energy installations are increasingly being integrated with Power-to-Gas technologies to generate "green hydrogen." This is particularly pertinent considering the ongoing energy transition. Because of the ongoing energy transition, hydrogen has been recognised as an essential component of a carbon-free energy mix. This is owing to its ability to play a vital role in the decarbonization of sectors resistant to change, energy storage and synthetic fuels. This repurposing of existing offshore infrastructure for dedicated hydrogen production hubs is a major step forward in marine systems engineering [78].

Hydrogen can be produced through offshore renewable energy systems. For example, offshore wind can generate electricity. This electricity can then power an electrolysis system to produce hydrogen gas from water. The produced hydrogen gas can be transported through pipelines or stored and transported through the application of a hydrogen vessel. These hydrogen products can then be used for various purposes, including fuel cells and gas turbines for power generation. As shown in the process flow diagram in Fig. 5 below, the repurposed deck space that is available on the platform allows for the integration of the entire gamut of the hydrogen production process,

whereby renewable electricity is used to power water treatment and electrolysis systems, producing hydrogen and oxygen from purified water. This specific configuration illustrates a 50 MW electrolysis plant alongside hydrogen storage tanks capable of holding 100 tonnes of hydrogen. This hydrogen is transported via existing subsea pipeline infrastructure connecting it to an existing 12-inch subsea export pipeline. Existing subsea gas pipelines can be repurposed but require hydraulic and materials assessment. Transport capacity depends on diameter, pressure and compressibility. A 12-inch pipeline operating at high pressure may transport on the order of tens to low hundreds of tonnes of hydrogen per day, depending on operating pressure, temperature and allowable hydrogen concentration [79-80]. In essence, this extends the useful life of the existing oil and gas pipeline logistics infrastructure.

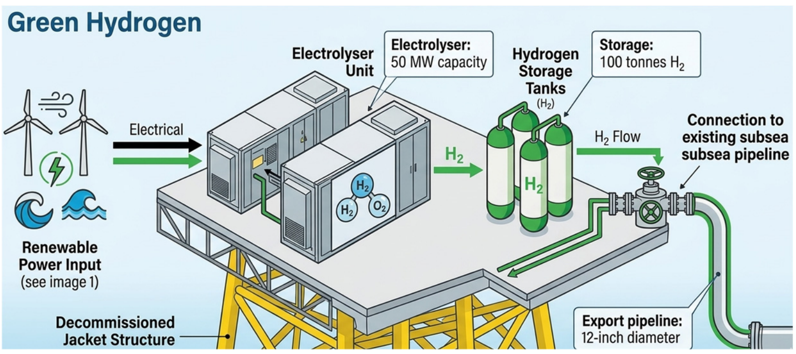

Figure 5: Schematic of an offshore green hydrogen production system integrated onto a repurposed platform, showing the flow from electrolysis to subsea pipeline export. Schematic created by the authors based on offshore hydrogen and Power-to-X concepts reported in [79-83]

The repurposing of existing fixed jacket platforms for offshore electrolysis offers significant logistical and economic benefits. Firstly, the existing topside facilities may have considerable deck space and structural payload capacity to support the significant weight requirements of the modular skid systems required for the electrolysis process, compressors, and power electronics. Nevertheless, a major engineering constraint is the large load that these modules are expected to carry. A commercial electrolyser with factory-built 1–5 MW modules is commonly containerised, complete with the necessary water purification and compression modules and puts an extremely high structural deck load, which normally varies between 2 and 6 kN/m² depending on layout and storage tanks [81-82]. As such, it is imperative to conduct a finite element analysis on the structure to guarantee its structural integrity against such loads. Secondly and most significantly, existing fixed platforms are already physically connected to extensive subsea pipeline systems. Rather than installing expensive high-voltage direct current electrical export cables, existing offshore gas pipelines could be repurposed to transport compressed hydrogen gas directly to onshore facilities, which is a concept currently being pioneered by projects in the North Sea [83].

Despite these advantages, hydrogen production still creates major engineering challenges. Hydrogen gas is highly volatile, has low density and a wide flammability range. Because of these properties, strict safety procedures are needed. Major blast wall upgrades may also be required to meet modern hazard requirements for ageing structures. Hydrogen transport through ageing pipelines poses a severe risk of hydrogen embrittlement. The hydrogen embrittlement (HE) is a significant hazard to carbon steel in ageing pipelines and jacket sections. Recent studies indicate accelerated crack propagation and embrittlement of X-grade steels at elevated hydrogen concentrations under cyclical loading, while the embrittlement thresholds depend on microstructure, stress intensity and hydrogen fugacity [84]. The mitigations include pipeline requalification, lining or interior coating, cathodic protection assessment and hydrogen pressure restriction or blending pending materials validation. Consequently, extensive pipeline requalification and jacket structural integrity management (SIM) are necessary to accommodate the immense loads of the new chemical plant [37]. Despite the challenges, the idea of offshore green hydrogen production has gained significant attention from the research community and other stakeholders, given the potential for large-scale use of renewable energy. Thus, the use of decommissioned offshore platforms for hydrogen production is an emerging research area with significant potential for sustainable offshore energy.

5. Structural feasibility of repurposing jacket platforms

The repurposing of offshore platforms for renewable energy applications would need a rigorous, data-driven assessment of the feasibility of the structures [9, 71]. While offshore platforms were built to extract oil and gas resources from the seabed, the structural frameworks of these platforms offer a promising foundation for the support of renewable energy applications [75]. However, the structural performance of offshore platforms built for renewable energy applications would be entirely different from that of platforms built with oil and gas extraction in mind [4]. Therefore, the feasibility of repurposing offshore platforms would be determined by three factors [7]. These factors include the structural integrity of the platforms, the suitability of the platforms to support new structures and the techno-economic feasibility of modifying the structures where necessary.

Fortunately, offshore platforms approaching the end of their production life still retain substantial structural capacity [11]. The oil and gas jackets are designed to be over-engineered

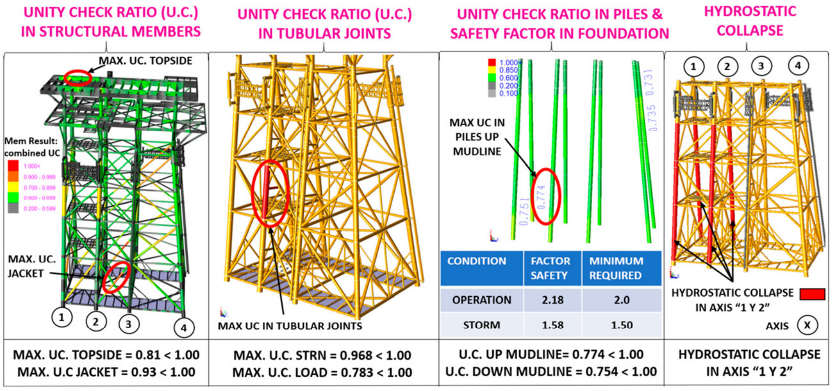

Figure 6. Numerical Modelling and Structural Integrity Analysis of an Offshore Jacket Platform, reproduced from Martínez et al. [87] under the terms of the Creative Commons Attribution (CC BY) license

with high safety factors to withstand 100-year extreme environmental conditions. The structural capacity utilisation ratio (UR), which measures the ratio of stress to ultimate load-bearing capacity, is often maintained below 60% to 70% for the primary jacket legs during the operational life [28]. The drastic reduction in topsides such as heavy and multiple-level hydrocarbon processing units, significantly reduces the structural capacity utilisation ratio and results in a structural allowance for new renewable energy equipment. This residual capacity provides an important opportunity for repurposing initiatives, particularly when the cost of complete removal is considered [85].

Several numerical case studies on the standard 4-legged jacket structure, which was installed at a water depth of 50 m provide a clear metric for feasibility [86]. In a recent study, Zendehdel & Khedmati [23] demonstrated that the replacement of a traditional 2500-tonne oil and gas platform topside with a 5 MW offshore wind turbine resulted in a considerable reduction in the static axial loads on the structure [86]. However, the new aerodynamic thrust introduced higher dynamic overturning moments on the structure. Finite element analysis (FEA) established that the change in loads resulted in a significant increase in the maximum utilisation ratio of the critical splash zone tubular joints. Since the maximum UR remains well within the 1.0 structural yield threshold, the repurposing proved structurally feasible without requiring significant reinforcement works [6, 26].

Nevertheless, it is important to recognise that structural degradation may occur during decades of exposure to harsh marine environments [23]. Repurposing strategies should not assume that existing offshore platforms are directly suitable for new applications. A detailed structural assessment is required to determine whether the platform can safely support additional equipment and operational loads associated with renewable energy systems [13].

5.1 Structural integrity assessment

The first step in assessing whether an offshore platform can be repurposed is to evaluate the structural integrity of the existing structure [71]. Structural integrity assessments aim to determine whether the platform can continue to operate safely under future loading conditions. The feasibility of repurposing mainly depends on the residual capacity of the structure. Engineers can use numerical modelling to calculate the Unity Check (U.C.) ratios for critical components. As shown in Fig. 6, a U.C. ratio below 1.00 indicates that structural members, tubular joints, and foundation piles possess the safety margins necessary to withstand the additional dynamic loads introduced by new renewable energy equipment [9].

Visual inspections and non-destructive testing techniques are commonly used to identify structural damage such as corrosion, cracks, and deformation in key structural components [28]. A key prerequisite for any repurposing decision is determining the as-is structural condition of the ageing jacket. Since decommissioned platforms may have experienced decades of corrosion, fatigue damage, accidental impacts, marine growth, scour and possible degradation of cathodic protection systems, the original design conditions cannot be assumed to remain valid [6, 87]. Non-destructive testing (NDT) should be treated as a mandatory baseline activity before structural reanalysis. Typical methods include ultrasonic thickness measurement for wall-loss mapping, magnetic particle inspection or alternating current field measurement for surface-breaking cracks, radiographic testing for hidden defects, cathodic protection potential surveys and ROV- or diver-assisted visual inspection of underwater members and tubular joints [6, 87]. The inspection results should be used to update finite element models, corrosion-fatigue assumptions, member capacity, joint integrity and reliability-based remaining useful life estimates. This as-is model updating process provides a defensible engineering basis for deciding whether repurposing, retrofit or full decommissioning is the most appropriate option. Critical areas usually receive special attention during structural assessment. These areas include welded joints, tubular intersections and load-bearing members within the jacket framework. These locations often experience high stress concentrations and are more likely to develop fatigue damage [30].

Physical inspection is also supported by structural analysis. This analysis is usually carried out using numerical modelling methods. Finite element models can be developed to simulate the behaviour of the platform under different loading conditions. These conditions include environmental loads and operational loads from renewable energy systems. This type of analysis can show how stress is distributed within the structure and help identify weak areas that may need reinforcement [11].

From a practical view, structural integrity assessment is important in deciding whether repurposing is suitable for a specific offshore platform. In some cases, structural degradation may be too severe to support repurposing. This is especially true when major repairs or structural replacements are required. If the platform remains structurally sound, repurposing may be a cost-effective and environmentally beneficial option compared with complete removal [7].

Early-stage structural screening methods may also be useful in future research. Standardised assessment frameworks for repurposing potential can help operators quickly determine whether a platform is suitable for conversion to renewable energy applications [85].

5.2 Load changes under renewable energy systems

One major engineering challenge in repurposing an offshore platform for renewable energy is the change in loading conditions [75]. Offshore platforms built for oil and gas production are usually designed to resist different environmental loads such as waves and wind. When renewable energy systems such as wind turbines are added, new types of loads may be introduced. These loads can change the behaviour of the whole structural system [9]. This change in structural demand can be checked using the Unity Check (U.C.) formulation, which ensures that the combined axial and bending stresses remain within safe limits.

$$U.C. = \frac{f_a}{F_a} + \frac{C_m \cdot f_b}{(1 - f_a/F_e')F_b} \leq 1.0 \tag{11}$$

where U.C. = Unity Check (Ratio of actual stress to allowable stress; must be ≤ 1.0), f_a = Calculated axial compressive stress, F_a = Allowable axial compressive stress, f_b = Calculated bending stress, F_b = Allowable bending stress, C_m = Moment reduction coefficient (accounts for stress distribution), $F'e$ = Euler buckling stress (divided by a safety factor) [88]

For instance, offshore wind turbines have rotating blades that are subject to significant aerodynamic forces. These forces are transferred up the tower and will impose additional bending and dynamic loads on the offshore platform. The size, direction, and rate of these forces may be quite different from those that the offshore platform was originally designed to accommodate [4]. As might be noted from the comparative schematic in Fig. 7, the "Original Oil & Gas Platform" is fundamentally "Gravity Dominated," transferring "Gravity Loads" based on the weight of the topside structure. On the contrary, the "Repurposed Wind Turbine Platform" is "Thrust Dominated," transferring "Rotor Thrust".

$$ULS\ Load\ Combinations = \sum_{j\geq 1} \gamma_{G,j} \cdot G_{k,j} + \gamma_{Q,1} \cdot Q_{k,1} + \sum_{i>1} \gamma_{Q,i} \cdot \psi_{0,i} \cdot Q_{k,i} \tag{12}$$

where ULS=Ultimate Limit State, γ_G = Partial factor of the dead load, G_k = Dead load, $\gamma_{Q,1}$ = Partial factor of the leading variable action/load like live, snow or wind load, $Q_{k,1}$ = Leading variable action, $\gamma_{Q,i}$ = Partial factor of the accompanying actions/loads like live, snow or wind load, $\psi_{0,i}$ = Psi factor of the accompanying actions/loads and $Q_{k,i}$ = Accompanying variable action [89].

Eq. (12) is presented as a generic partial-factor ULS load-combination format based on EN 1990. The offshore-specific load cases and partial factors should ultimately be selected according to ISO 19902, API RP 2A-SIM and project-specific design criteria [6, 89].

This addition can result in a 30% to 50% increase in maximum bending moments in the jacket legs compared to the original oil and gas specifications [90]. Wind turbines introduce cyclic

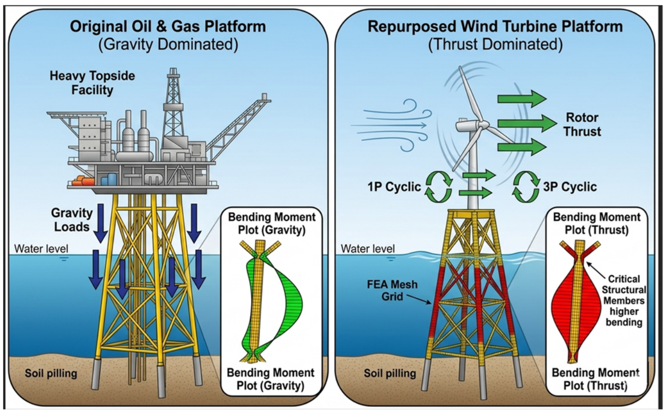

Figure 7. Conceptual and analytical comparison of structural loading between the original Oil & Gas platform (Gravity Dominated) and the repurposed Wind Turbine platform (Thrust Dominated). Schematic created by the authors based on offshore wind repurposing and dynamic loading concepts discussed in [4, 68-70]

loading due to the rotation and wind fluctuations. These cyclic loadings may cause a faster rate of fatigue in the structural members. Bhattacharya [91] suggests that turbine integration can lead to a 2x to 5x increase in fatigue cycle accumulation. Hence, fatigue life assessments may be required to ensure that the existing structure can withstand the increased number of load cycles imposed by the wind energy system [30].

Wave and tidal energy devices may also impose additional hydrodynamic loads on offshore platforms. Devices attached to the jacket structure may interact with wave motion and tidal currents, potentially altering the hydrodynamic forces acting on the platform. This interaction occurs because added hardware increases the effective projected area and displaces the volume of the submerged members.

Specifically, the addition of external equipment creates a “blockage effect” that enhances flow turbulence. This can result in a 15% to 25% increase in horizontal base shear during peak tidal flow [75]. This interaction needs to be critically evaluated to ensure that stability and a U.C. ≤ 1.0 is maintained, as the original jacket legs were not sized for this type of "catch" from the energy-capturing surfaces.

In the context of repurposing projects, a detailed load analysis is necessary for a better understanding of the interaction between the renewable energy equipment and the structural behaviour of the repurposed platforms. For a better understanding of the interaction, complex simulation techniques and aero-hydro-structural models are considered. The analyses are necessary to ensure that repurposed platforms can meet modern safety and reliability requirements [71].

5.3 Structural retrofitting and reinforcement

If structural assessments indicate that the existing platform cannot fully accommodate new loading conditions, structural retrofitting measures may be required [92]. Retrofitting refers to the process of modifying or strengthening the existing structure to improve its load-bearing capacity and structural performance. Common retrofitting strategies for offshore jacket platforms may include reinforcing critical structural members, adding additional bracing elements or strengthening connections within the jacket framework. In some cases, the platform deck may need to be modified to support new equipment such as wind turbine towers, power conversion systems or hydrogen production units [9].

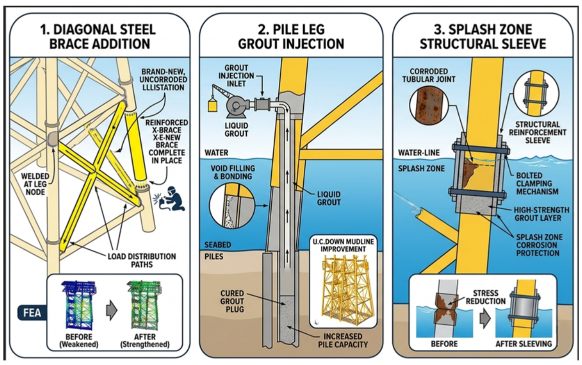

Figure 8. Detailed technical schematic of three key offshore jacket retrofitting techniques: (1) Diagonal Steel Brace Addition; (2) Pile Leg Grout Injection; (3) Splash Zone Structural Sleeve. Schematic created by the authors based on offshore jacket retrofitting techniques reported in [9, 23, 35, 92]

Fig. 8 shows that these measures generally involve three main techniques and each results in measurable improvements to the structural performance. First, diagonal steel X-bracing is used to ensure a level of redundancy. Recent finite element analysis results indicate that this can improve the global lateral stiffness and ultimate pushover capacity of the platform by 25% to 40%. This improvement can help resist the extreme overturning moments imposed by wind turbines [23]. Second, liquid grout can be injected into the aged pile legs to fill the existing annular voids and bond the structure more effectively to the mudline. This method can improve pile capacity and buckling resistance by 30% to 50% [9]. Lastly, structural reinforcement sleeves with bolted clamping systems can be used in the highly corrosive splash zone to help reduce stress concentration factors (SCFs) at weakened tubular joints. This particular action is crucial for life extension as it may increase the local fatigue life of weakened nodes by an estimated 15 to 20 years without requiring complicated underwater welding operations [35].

Aside from jacket substructure reinforcement, platform decks also often need extra support structures or transition pieces. These modifications are important for distributing loads more effectively between the renewable energy system and the existing platform structure. They also help distribute the weight of new topside equipment more evenly through the main legs such as a power conversion system or a hydrogen production system [11]. By effectively reducing localised deck stresses and maintaining strict dynamic decoupling, these supplementary interfaces can support the fatigue life extension of the repurposed asset.

From an economic perspective, the feasibility of these structural improvements must be compared with project capital expenditure (CAPEX). Although extensive retrofitting such as deep-water grouting or massive brace upgrades significantly enhances strength and fatigue performance, excessive offshore interventions can reduce the cost savings expected from repurposing rather than building new offshore facilities [4, 95]. Therefore, future engineering research should focus on optimised retrofitting solutions for repurposed offshore platforms. Standardised retrofit modules or adaptable structural interfaces could significantly reduce the complexity and cost of platform conversion projects [75].

5.4 Foundation and seabed considerations

The foundation system of an offshore platform plays a critical role for structural stability. For fixed jacket platforms, the foundation typically consists of steel piles driven deep into the seabed to provide resistance against environmental and operational loads. When a platform is considered for repurposing, the existing foundation system must be assessed to confirm whether the foundation can safely support new loading conditions [7].

Renewable energy installations can alter the structural loads acting on the platform, which may affect the way loads are transferred between the platform structure and the seabed. For instance, large wind turbines can introduce extra overturning moments that the foundation piles must resist. Soil-Structure Interaction (SSI) must be assessed using non-linear p-y curves, which define the relationship between soil resistance (p) and pile deflection (y). As illustrated in Fig. 9, soil response can vary greatly under different conditions, while non-liquefied soil (Curve A) provides robust resistance. Dynamic loading can cause soil liquefaction (Curve B), drastically reducing resistance. Modern hardening models (Curve C) are utilised to consider post-liquefaction resistance, which is vital for determining the ultimate capacity of the foundation system [93-95]. If these loads exceed the original design capacity, reinforcement or foundation modifications may be required [23].

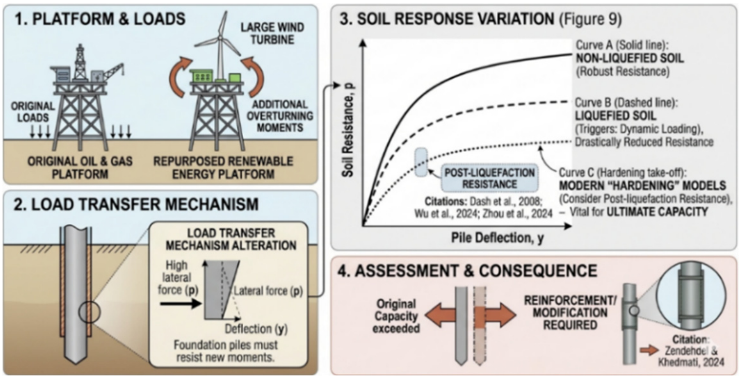

Figure 9. Integrated soil-structure interaction (SSI) assessment for offshore platform repurposing. Schematic created by the authors based on nonlinear p-y curve concepts, liquefaction-related soil response and foundation repurposing assessment criteria reported in [23, 93-95]

Table 5. Technical Criteria for Repurposing Feasibility Assessment

Assessment Factor	Key Methods	Critical Metrics	Acceptability Criteria
Structural Integrity	Non-Destructive Testing (NDT), Finite Element Analysis (FEA)	Unity Check (UC) ratio	UC < 1.0
Load Analysis	Aero-hydro-elastic simulations; Pushover analysis	Reserve Strength Ratio (RSR)	RSR > 1.5 (per ISO 19902)
Retrofitting	Structural bracing, Grouting, Life extension analysis	Stress concentration reduction	Cost-benefit ratio vs. Decommissioning
Foundation Capacity	Geotechnical analysis; SSI modelling (p-y curves)	Pile Safety Factor (SF); Scour Depth	SF > 2.0 (per API RP 2SIM)

Geotechnical conditions also play an important role in determining foundation performance. Seabed conditions may change over time due to sediment movement, scour effects or other environmental processes. Hence, updated geotechnical assessments are often necessary to evaluate the current condition of the seabed around the platform. They should also consider scour depth, since scour may reduce the effective embedment and lateral stability of the piles [11].

In many cases, offshore platform foundations are designed with significant safety margins. This means the existing piles may still possess adequate capacity to support moderate increases in structural loading. Nevertheless, detailed geotechnical analysis is essential to verify the stability of the foundation before implementing repurposing projects [13]. The key assessment factors and their acceptability criteria for this feasibility phase are summarised in Table 5. Specifically, a Reserve Strength Ratio (RSR) > 1.5 is often used as an indicative screening benchmark. This value shows that the platform can resist loads 50% higher than the design environmental load before reaching a collapse mechanism. This criterion is consistent with ISO 19902 standards for "High Consequence" structures. Furthermore, a pile Safety Factor (SF) > 2.0 may also be used as a conservative preliminary criterion to account for the uncertainty of soil behaviour. This covers uncertainties in sampling, ageing effects and unexpected scouring [6].

These values should be interpreted as indicative screening criteria rather than universal acceptance thresholds, since the required safety margins depend on consequence class, jurisdiction, inspection reliability and site-specific loading conditions. Foundation assessment is one of the most important steps in evaluating whether an offshore platform can be reused. Structural modifications above the waterline may be more straightforward. In contrast, foundation upgrades are often technically difficult and costly. Consequently, platforms with strong and well-preserved foundations are generally more suitable candidates for repurposing initiatives [7].

6. Engineering challenges in platform repurposing

Despite the promising potential of the repurposing of the existing offshore structures for the implementation of renewable energy technologies, certain engineering challenges must be taken into consideration [4, 37]. First, the existing offshore structures were initially designed for hydrocarbon production rather than renewable energy applications. It may also not directly satisfy the operational, structural and safety requirements of ORE systems [92]. To overcome the engineering challenges, certain modifications must be made to the existing structures to comply with the newly imposed operational conditions [28]. Moreover, the lifespan of the existing offshore structures is quite long and this factor is associated with certain uncertainties [23].

The most critical engineering problem, which serves as a main barrier, relates to the basic incompatibility in terms of operational load patterns. For instance, when retrofitting a jacket structure to accommodate an offshore wind turbine (OWT), there are dynamically fluctuating aero-elastic load patterns that were never meant to withstand such a condition in tubular structures. This creates a critical problem from a technical standpoint and engineers are faced with a critical problem related to dynamic coupling, whereby they are obligated to ensure that the natural frequency of an ageing jacket structure remains decoupled from the rotational frequency ranges of massive wind turbine blades to avoid catastrophic resonance [23, 91]. In addition, safely deconstructing the existing hydrocarbon topsides and constructing new transition pieces requires complex structural retrofitting without diminishing the Remaining Useful Life (RUL).

Secondary to these technical issues is the substantial cost factor of offshore modifications. While the technical aspects of a repurposing design are feasible, the cost factor can soon overshadow the project's viability. Repurposing an existing offshore structure demands the use of specialised vessels called Heavy Lift Vessels (HLVs) and saturation diving crews to reinforce the underwater nodes of the structure. If the foundation piles and the significant spatial braces need considerable strengthening to resist the overturning moments of the renewable energy systems being installed, the capital expenditure (CAPEX) of the repurposing project can sometimes approach or exceed the total cost of traditional decommissioning and constructing a new purpose-built structure [52]. Cost overruns are an extremely high-impact issue with decommissioning projects having an average of 76% excess budgets, thereby increasing the economics uncertainty of repurposing projects, particularly when regulatory requirements and offshore intervention scopes change during project execution [96-97].

Another emerging challenge is the operation of repurposed offshore platforms as normally unattended or minimally manned stations. Unlike conventional production platforms, renewable energy hubs, offshore hydrogen facilities, CO_2 injection stations or refuelling hubs may rely heavily on remote operation and continuous condition monitoring. Therefore, sensor-assisted and AI-based structural health monitoring should be incorporated into future repurposing frameworks.

Accelerometers, strain gauges, corrosion probes, environmental sensors, SCADA data and fatigue-sensitive joint monitoring can be integrated to track changes in dynamic response, corrosion progression and local damage accumulation [6, 98]. Recent machine-learning studies on wind turbine condition monitoring have shown that ANN, LSTM and sensor-reduction techniques can predict unavailable or non-functional sensor signals and support fatigue tracking [98]. Although the cited study focuses on wind turbine pitch-bearing monitoring rather than jacket substructures, it demonstrates the broader relevance of ML-based sensor reduction for remote offshore condition monitoring. Such approaches are particularly relevant for repurposed jacket platforms, where sensor availability, maintenance access and offshore inspection frequency may be limited. AI-assisted monitoring should therefore complement NDT-based as-is assessment and reliability-based inspection planning throughout the extended service life [87, 98].

Lastly, compounding both technical and economic hurdles is the tertiary problem of structural uncertainty. After 20 to 30 years of exposure to a hostile marine environment, there is often a significant discrepancy between the "as-built" engineering design and the current "as-is" condition of the offshore jacket structure [35]. Hidden fatigue micro-cracks, undocumented damage resulting from accidental collision and different levels of localised pitting corrosion contribute to a high level of risk within the reliability model. Additionally, the lack of universally accepted and standardised regulations for repurposed platforms means that engineers face a complex and uncertain process to certify that the ageing structure is still safe for a second life [4].

6.1 Corrosion and structural degradation

The structures are always exposed to harsh environmental conditions such as seawater, wind and temperature variations [7]. This leads to the deterioration of structures over a period. This deterioration could be in the form of corrosion or fatigue failure [23]. Offshore structures nearing the end of their life have been in use for more than three decades. Thus, it can be concluded that such structures are highly prone to deterioration [28].

One of the most common reasons for the deterioration of steel structures in offshore structures is corrosion [11]. Structures are always in contact with seawater. This leads to corrosion of steel structures over a period. This results in the reduction of the thickness of steel structures. Although coatings are applied to structures to avoid corrosion, such structures are highly prone to corrosion over a long period of time.

Another important factor of damage would be fatigue damage [20]. The offshore platforms will be subjected to repeated load conditions and this will cause cracks in the joints of the structure. With time, this will cause further cracks in the structure of the offshore platform.

From an engineering point of view, it is evident that the damage caused by corrosion and fatigue will not hinder the repurposing of the structure. In fact, repairs will be necessary for repurposing the structure [27]. In the future, research can be conducted on how to develop an advanced monitoring system, such as a structural health monitoring system [20].

6.2 Integration with renewable energy systems and maintenance issues

Another significant challenge is associated with the integration of renewable energy systems and existing offshore structures [37]. Most of the oil and gas structures were developed with the primary aim of accommodating drilling rigs and production equipment for oil and gas production.

Table 6. Engineering Challenges Summary

Challenge Area	Primary Issues	Engineering Solutions
Corrosion/Fatigue	Thickness loss, crack propagation	SHM, weld repairs
Integration	Layout mismatch, dynamic loads	Deck mods, EMS upgrades
Operations	Access, new inspections	Safety upgrades, planning
Regulatory	Removal mandates	Policy revision

In addition, the configuration and layout of the existing oil and gas structures may not be easily compatible with renewable energy systems [92].

For example, wind turbines require a specific configuration for the transfer of wind energy. Integrating wind turbine towers into existing structures may require modifications to the deck structures [4]. Similarly, wave and tidal energy devices require installation on the structures or near the foundation of the structures. These structures may require a specific design to ensure that they do not interfere with the hydrodynamic response and stability of the structures [75].

Another technical factor to consider is the electricity infrastructure. In fact, electricity generated in a renewable energy system must be transmitted to land or be used to power offshore facilities like hydrogen plants. However, it should be noted that the electricity infrastructure in platforms might not have enough capacity to meet new requirements; thus, more electric management systems might have to be included [83]. According to this view, the success of integrating renewable energy systems into offshore platforms depends on cooperation between various parties [99].

Regular inspection, maintenance and repair operations must be carried out for offshore renewable energy systems [20]. When renewable energy technologies are installed on repurposed offshore platforms, the operational requirements of the platforms may change compared to their original operational requirements [20]. For example, wind turbines installed on offshore platforms may require periodic inspection of mechanical wind turbine structures and electrical systems. Wave and tidal energy technologies may require underwater maintenance operations for optimal functionality. The operational requirements for wave and tidal energy technologies may change compared to their original operational requirements [37]. Repurposed platforms may have some support structures for maintenance operations, such as accommodations, helidecks, and storage spaces. The long-term operational requirements for offshore renewable energy platforms must be planned carefully to ensure optimal functionality.

Another challenge is related to the accessibility of ageing platforms. There exists a possibility that such platforms could require upgrading of their safety equipment, routes of access, and response gear before they can be utilised in the generation of renewable energy [4]. Moreover, the potential of the platform could be a factor that influences the success of the project related to the platform's ability to support efficient maintenance activities in some cases [72].

6.3 Regulatory and safety considerations

Another factor associated with repurposing offshore platforms is the regulations and safety issues [100]. There are various regulations and guidelines associated with offshore structures such as safety regulations for structures, environmental regulations, and operational regulations. These regulations and guidelines will have to be considered in repurposing offshore structures from hydrocarbon production facilities to offshore renewable energy production facilities.

There are some regulations in some countries on the decommissioning of offshore structures. These regulations require that offshore structures be removed after production activities have stopped [101]. These regulations and guidelines on the removal of offshore structures were initially developed to minimise the impact of offshore structures on the environment and marine traffic. However, these regulations and guidelines on the removal of offshore structures after production activities stop may hinder offshore platform repurposing possibilities [100]. With the current interest in offshore renewable energy production, regulations and guidelines on decommissioning offshore structures will likely be revisited [100]. The primary regulatory and operational challenges are summarised in Table 6**.**

Considering offshore platform repurposing from a sustainability point of view, it is beneficial in various ways such as minimising the impact on the environment and saving on decommissioning offshore structures [4, 9, 95].

7. Case studies of repurposed offshore platforms

Although commercialisation activities are still in the early stages, recent pilot projects and conceptual studies confirm that old offshore structures can be repurposed to transform liabilities into vital renewable energy assets [52]. An evaluation of these projects has revealed three important themes related to cost savings, structural modifications and lessons learned. From a cost perspective, repurposing structures helps avoid huge capital expenditure (CAPEX) associated with building new foundations and postpones the total costs associated with decommissioning. In fact, recent economic assessments of pilot projects indicate that utilising existing subsea foundations and jacket structures can reduce the initial CAPEX of offshore renewable installations by 20% to 40% [52], provided that associated costs related to marine logistics do not escalate beyond those associated with new-build expenses [43]. On a structural front, repurposing structures involves complex activities, including topside de-oiling and removal, installation of custom transition pieces and joint strengthening to accommodate dynamic load conditions associated with renewable technologies. One important lesson learned from these projects has been the absolute importance of condition assessments, whereby discovering a discrepancy between original "as built" and "as is" conditions during a project can destroy its financial viability, a factor often contributed to by a

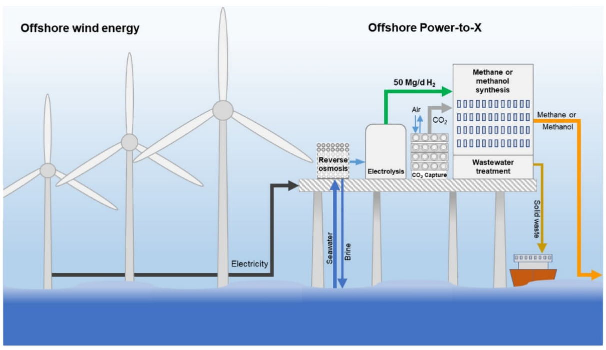

Figure 10. Offshore platform integrated with wind turbines for Power-to-X such as hydrogen, demonstrating hybrid repurposing concepts for renewable energy conversion, reproduced from Morales et al. [102] under a CC BY 4.0 License

lack of standardised certification processes [4]. Besides providing the infrastructure required by traditional wind farms, these structures have immense potential as multi-functional green energy platforms. This can be exemplified by the potential of these structures to host 'Power-to-X' (PtX) facilities, as shown in Fig. 10 [102]. This would allow the nearby offshore wind farms to provide the required power for reverse osmosis and electrolysis of water to produce green hydrogen (H_2). This can then be synthesised into transportable green fuels such as methane and methanol with the aid of carbon capture technology.

These case studies provide important insights into the technical potential, financial considerations and operational difficulties of platform repurposing. Large-scale implementation is still limited. Real-world examples can help researchers and industry stakeholders understand how existing offshore infrastructure may support the move toward sustainable offshore energy systems.

7.1 North Sea projects

Using existing offshore platforms to support offshore wind energy systems is one of the most widely discussed repurposing strategies [103]. Many ageing platforms are situated in areas with favourable wind resources. Some of these areas have well-established oil and gas infrastructure such as the North Sea [83]. This makes it possible to incorporate wind turbines into existing structures rather than build new foundations.

Several conceptual studies have proposed two main options. The first option is to install wind turbines directly on the topside deck of decommissioned jacket platforms. The second option is to use the platform as a support hub for nearby wind turbines [83]. In these arrangements, the existing platform can provide electrical infrastructure, maintenance facilities and structural support for wind energy operations. This strategy may reduce installation costs and speed up project development compared with constructing new offshore wind foundations.

For instance, some studies in the North Sea have proposed using abandoned oil and gas platforms as offshore wind service hubs [83]. In this case, the platform can serve as a central maintenance base for nearby wind farms. These repurposed platforms could house electrical substations and monitoring equipment. They could also provide space for maintenance crews and spare parts. From a practical view, integrating wind turbines with existing platforms requires detailed structural analysis [103]. Some platform structures may not be able to carry the extra loads from turbine operation. Structural retrofitting and reinforcement are often needed to ensure safe operation.

Repurposing platforms such as offshore wind farm support hubs may be more feasible than installing large wind turbines directly on existing structures. This method allows the platform to support the wind energy supply chain without placing undue structural strain on it.

7.2 Gulf of Mexico reuse initiatives

Converting decommissioned offshore platforms into multi-energy hubs that support various renewable energy technologies at once is another emerging repurposing idea [104]. Instead of relying on a single energy source, these hybrid systems combine different marine renewable technologies. This can improve overall energy efficiency and reliability.

In this type of system, offshore wind turbines may act as the main energy source. Tidal turbines and wave energy converters can also provide extra electricity [105]. The repurposed platform can serve as a central hub for collecting, processing and transmitting electricity from various energy systems to shore or offshore for uses such as hydrogen production.

Table 7. Repurposing Projects Comparison

Region	Key Examples	Technology	Implementation Status
North Sea	UKCS platform → H2 hub	Wind service hubs, Green H2	Pilot/Feasibility studies
Gulf of Mexico	1500 platforms assessed	Hybrid wind-tidal mariculture	Conceptual/ROICE projects
SE Asia	Malaysia/Indonesia platforms	Future offshore wind	Emerging potential

This idea has received more attention in recent years because it enables current offshore infrastructure to contribute to future integrated offshore energy systems [104]. Hybrid energy hubs have the potential to reduce the need for new offshore structures, while optimising the use of available marine resources by combining various renewable technologies. For instance, some European offshore energy research projects have proposed using existing oil and gas platforms as control centres for nearby renewable energy installations [104]. These platforms could house energy storage technologies, monitoring systems and power conversion equipment. This arrangement can support better management of offshore energy production.

However, multi-energy offshore hubs also create new technical challenges. This requires sophisticated system coordination, power management systems and strong structural design to integrate several renewable energy technologies into a single offshore infrastructure. The economic feasibility of these hybrid systems also needs further study. The idea of repurposing offshore platforms as multi-energy hubs supports the wider goal of integrated offshore energy networks. These networks combine renewable energy production, storage and distribution.

7.3 Emerging concepts for hybrid energy platforms

The viability of offshore platform repurposing differs across regions because offshore infrastructure, environmental factors and renewable energy potential vary from one region to another [106]. Table 7 shows this regional comparison of repurposing projects. Areas with large offshore oil and gas activities usually have many ageing platforms that could be good candidates for repurposing projects. The North Sea is one of the main regions where platform repurposing has been actively studied [83]. Over several decades, nations like the Netherlands, Norway and the United Kingdom have built substantial offshore energy infrastructure. Researchers and policymakers have started looking into ways to incorporate these platforms into new offshore renewable energy systems, as many of them are near the end of their useful lives.

Similarly, regions in Southeast Asia that possess a certain level of offshore oil and gas activity can also benefit from repurposing strategies [106]. Malaysia and Indonesia, for instance, possess many offshore platforms in their regions where renewable energy resources such as wind and wave energy can be harnessed in the future. Although the development of large-scale offshore renewable energy in these regions is still in its nascent stages, repurposing strategies for existing infrastructure could reduce barriers to entry. In tropical regions such as Southeast Asia, offshore solar and hybrid solar-wind systems may provide supplementary power for platform self-consumption, monitoring systems and low-power auxiliary loads. However, large-scale deployment remains constrained by salt spray, marine fouling, maintenance access, typhoon exposure and limited deck area [107-108].

The regional variations in infrastructure and policies are likely to play an important role in determining the success of repurposing strategies for platforms. Although some regions may emphasise the complete removal of platforms for environmental or policy reasons, others may gradually recognise the importance of repurposing strategies as an important component of sustainable offshore energy development. Overall, the case studies show that decommissioned offshore platforms have strong potential to support the global shift toward renewable energy.

8. Conclusions

The repurposing of decommissioned fixed jacket offshore platforms is more than a conceptual sustainability option. It is a quantifiable and strategic imperative in marine infrastructure management. Global decommissioning liabilities are expected to reach hundreds of billions of dollars. Hence, complete structural removal is becoming difficult to justify from both economic and environmental views. This analytical review demonstrates that repurposing existing steel substructures for offshore renewable energy (ORE) is consistent with circular economy principles. Some studies report approximately 20% to 40% lower initial capital expenditure (CAPEX) compared with new-build foundations. This approach may also help reduce the Levelised Cost of Energy (LCOE) for offshore power generation.

From a technical perspective, offshore wind power grid connection remains the most mature retrofit approach. This transformation fundamentally changes the structural requirements on the platforms. The structure is no longer mainly affected by static gravity loads but by highly dynamic aerodynamic thrust, which is usually between 1.0 and 2.0 MN. Wave and tidal hybrid systems are still at lower technology readiness levels (TRL), but the integration through modified Morison equation hydrodynamic parameters offers a possible route for baseload power generation. Furthermore, offshore hydrogen production shifts the utilisation envelope entirely. It requires topside deck framing that can support payloads above 2 to 6 kN/m^2. It also requires strict metallurgical thresholds to maintain hydrogen partial pressures and to prevent embrittlement in existing export pipelines.

Fundamentally, the viability of any repurposing project mainly depends on the structural reliability of the degraded asset. This review emphasises that general structural reassessments are insufficient for safety-critical repurposing decisions. Instead, rigorous Aero-Hydro-Servo-Elastic (AHSE) coupled analyses are necessary for safety-critical repurposing assessments to evaluate dynamic amplification factors (DAF). It should also confirm proper frequency separation from the rotor-rotation (1P) and blade-passing (3P) excitation bands. This requirement is important because legacy jackets have already experienced decades of cyclic wave loading and local splash-zone corrosion. Remaining Useful Life (RUL) assessments must utilise probabilistic fracture mechanics and calibrated S-N fatigue curves. The structural capacity utilisation ratio (UR) under these novel load combinations shows an important trend. The primary legs often remain within a safe range of about 0.60 and 0.70. However, heavily stressed tubular joints still require targeted and quantitative strengthening measures.

To move from conceptual feasibility to standard engineering practice, this review supports the use of a unified Reliability-Based Repurposing Framework (RBRF). This proposed decision model integrates quantitative structural health monitoring (SHM), Aero-Hydro-Servo-Elastic (AHSE) dynamic simulations and techno-economic optimisation to govern life-extension approvals. Within this framework, future research should focus on digital twin technologies. These technologies can use Bayesian updating for real-time fatigue tracking and damage detection. Furthermore, adaptive structural retrofitting should also be clearly quantified. For example, splash-zone sleeving may extend node fatigue life by 15 to 20 years, while pile grouting may increase axial capacity. These interventions must be assessed within ultimate limit state (ULS) and fatigue limit state (FLS) boundaries.

Future repurposing strategies should prioritise local offshore utilisation of generated power through hydrogen, ammonia, CO_2 sequestration, EOR, refuelling and platform self-powering applications rather than treating shoreward electricity export as the default pathway. For normally unattended repurposed stations, several measures should be treated as essential. These include NDT-based as-is condition assessment, reliability-based inspection planning and AI-assisted structural health monitoring. These measures are needed for safe long-term operation. Ultimately, technological feasibility must be supported by updated regulatory compliance. Transitioning decommissioned platforms from fossil fuel liabilities into ORE assets will require proper certification routes rather than reliance on case-by-case exemptions. The industry should move toward standardised and code-supported certification pathways. By coupling rigorous dynamic modelling with verified structural interventions, platform repurposing can become a potentially viable pathway within the sustainable ocean economy. However, this can only be achieved when site-specific structural, economic and regulatory conditions are satisfied.

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