

Review

# Incorporating Sustainability and Maintenance for Performance Assessment of Offshore Oil and Gas Platforms: A Perspective

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**Abstract:** The existence of external two-fold pressure regarding competitiveness and sustainable development in a capital-intensive industry supports the need for sustainable performance. However, endeavors to create a sustainable framework to measure the performance of the oil and gas (O&G) industry are mostly devoted to the production and supply chain of petrochemical products and rarely focus on a maintenance perspective. Motivated by such scarcity, the goal of this research was to discuss and articulate the performance assessment framework by integrating concepts of maintenance and sustainability in the O&G industry. This study proposed the use of a range of performance measures for assessing sustainability on offshore production and drilling platforms. The conceptual framework consists of four aspects of sustainability categorized into technical, environmental, social, and economic dimensions. Each measure was assigned according to its relevance at the strategic, tactical, and functional levels of maintenance decision making. The conceptual framework resulted in hierarchical clusters of twelve strategic indicators. These indicators consist of conventional measures as well as new ones relating to the safety and reliability on offshore platforms. The potential contribution of the present study is found in its intention to empower a better understanding of sustainable maintenance and encourage those making decisions about practical implementation within the O&G industry. This paper culminates with directions for future studies.

**Keywords:** conceptual framework; oil and gas industry; performance measures; sustainable development; sustainable maintenance



**Citation:** Olugu, E.U.; Wong, K.Y.; Chung Ee, J.Y.; Mammedov, Y.D. Incorporating Sustainability and Maintenance for Performance Assessment of Offshore Oil and Gas Platforms: A Perspective. *Sustainability* **2022**, *14*, 807. <https://doi.org/10.3390/su14020807>

Academic Editor: Víctor Yepes

Received: 2 August 2021

Accepted: 30 August 2021

Published: 12 January 2022

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## 1. Introduction

Within the oil and gas (O&G) production and drilling processes of today, there are challenges in maintaining the system for numerous reasons, ranging from international competition to market globalization, regulatory compliance [1], and the complexity brought by technological advancement [2]. Nevertheless, the higher competitiveness of the petrochemical market as well as the logistical and technical challenges of production and maintenance on offshore facilities necessitate devising acute planning and strategic decision-making processes [3]. This can generate a sustainable competitive edge while improving availability and productivity [4] and satisfying the requirements of stakeholders and regulatory bodies.

Furthermore, with the inflating maintenance costs and increasing failure frequency impacting production safety, the issue of non-sustainability in O&G companies is made worse by surplus or inefficient maintenance [5]. A previous paper [6] confirmed substantial costs associated with energy requirement in the development and maintenance of infrastructure in this industry. Thus, maintenance has direct sustainability-related impacts regarding social importance, influence on energy demand, exploiting physical resources, and environmental pollution [7]. Nevertheless, the rise in oil spills as a result of non-maintenance has indirect impacts, causing diverse damage of environmental assets, including species

extinction, vegetation and ozone layer depletion, and increasing poverty levels among host communities in the region [5]. Since the performance and competitiveness of an industry are affected by reliability [8] and environmental safety, it has become important to find a practical approach for sustainability and integrate it into maintenance processes [5].

This study aimed to develop a framework based on both sustainable production and maintenance as a performance function. Sustainable maintenance is an interconnected process designed to help sustain an asset by facilitating decision-making processes and their management, considering the influence on the social, economic, and environmental behavior within society as a whole [7,9]. Sustainable maintenance has further been described as an activity that supports the sustainability of an industry of technical factors and by reducing maintenance costs [10] without compromising the environmental and social wellbeing of personnel [11]. In general, sustainable maintenance has been suggested as an approach that includes environmental, economic, and social concerns [12,13]. However, operations in O&G facilities have potential effects on the environment along with safety, social, and economic consequences [13]. In order to address these problems, this study investigated sustainable maintenance in the O&G industry.

Sustainability in the O&G industry has been extensively investigated in the past few years [3,13–15]; however, few researchers have considered the concept of sustainable maintenance within this industry [5]. To address this obstacle, this research addressed both (i) studies on sustainability within the O&G industry and (ii) topics related to sustainable maintenance decision making by examining research gaps. First, the authors of [13] stated that O&G companies have systematic processes to reduce environmental impacts. However, these potential impacts include health, safety, social, and economic effects. The authors of [16] emphasized the social dimension in total productive maintenance where human capital is domain performance. It was reported that the occurrence of accidents was documented as a cause of hazard, danger, and socially isolated environments [17]. The authors of [18] highlighted the importance of human consistency in handling maintenance procedures on-board and stated that operating companies are required to invest in processes to improve maritime safety and environmental issues. As a supporting argument, the authors of [19] stated that maritime performance reliability is dependent on safety and loss prevention management, where the crew typically follows planned procedures. Second, recent studies on sustainable maintenance and performance indicators state that priority is given to the economic dimension at the detriment of the environmental and social dimensions [20]. Based on the argument of [21], we believe that it is still necessary to provide a balanced and comprehensive review of aspects relating to sustainability. Third, since sustainable maintenance is a new concept in the O&G industry, and implies that a multi-dimensional evaluation of the efficiency and effectiveness of maintenance processes on offshore production and drilling platforms is necessary. The authors of [22] suggested the use of Triple Bottom Line (TBL) evaluation to target overall equipment effectiveness and advocated the efficacy of the use of a maintenance strategy to assess industrial performance. Fourth, referring to the literature on sustainable manufacturing, the authors of [5] stated that a variety of dimensions were addressed and that little attention was paid to sustainable maintenance performance from a product lifecycle (PLC) perspective. The authors of [11] emphasized the need to consider the entire maintenance process as a separate subject. Other researchers have suggested the incorporation of dimensional analysis into the organizational structure and functional performance of maintenance management [12]. Thus, this study provides a holistic assessment of maintenance decision making at the strategic, tactical, and functional levels by revealing the impacts of technical, environmental, economic, and social dimensions for the implementation of sustainable practices in offshore settings.

The requirement for a conceptual framework is grounded in the intention that this study contributes to future work in this field. This research gathered information from various studies to enable a better focus on tackling the issues of competitive industries. Competitive environments are associated with sustainable production, which is reflected by legal regulations and financial advantage. In the literature review, this research focused

on studies incorporating these concepts that related to sustainable production and the supply chain [3,13] in the three-dimensional assessment of TBL for the O&G industry [5]. Therefore, this paper develops a perspective on sustainable maintenance that is based on the convergence of the paradigms of maintenance performance assessment and sustainable production. The contributions of this study are threefold. First, the current research was inspired by the systematic framework provided by [7] and aimed to extend it further to improve sustainable maintenance in the O&G industry. Second, the important finding regarding the association of maintenance performance and TBL of sustainability within the O&G industry from [5] was taken further to propose a four-dimensional evaluation that incorporated the technical dimension. Third, the authors of [12] suggested a hierarchical classification of TBL measures according to the three layers of sustainable maintenance decision making in the manufacturing industry. This study adopted this approach to classify twelve strategic indicators for the O&G industry as potential directions for the voluntary reporting of sustainability on offshore platforms.

The current research is organized as follows: Section 2 identifies studies related to sustainable performance assessment and maintenance management within the O&G industry. Section 3 illustrates the maintenance practices used on O&G offshore platforms. This is followed by Section 4, which proposes an assessment framework for sustainable maintenance processes for the offshore O&G industry. Key performance measures for offshore O&G platforms are proposed in this section. Finally, this research culminates with the conclusion and a list of potential future research opportunities.

## 2. Literature Review

In this section, a review of performance measurement concepts for sustainable maintenance is provided. Based on the previous literature, this review was guided by the necessity of identifying relevant papers published in Scopus listed in the following electronic databases: Emerald, ScienceDirect, and Elsevier. The study also made use of conference summaries. This research approach identified papers with the keywords “maintenance”, “sustainability”, “performance indicators”, “industry”, or “oil and gas” keywords in their title, abstract, or keywords. Subsequently, this study excluded papers that did not consider the problem of sustainable performance within their maintenance performance assessment to support the need for a sustainable maintenance performance assessment framework.

### 2.1. Sustainable Maintenance

Academic and industrial practitioners often refer to sustainable maintenance and sets of interconnected processes [7] to sustain assets during operation [11], reduce the impact of logistics on economic aspects, realize optimal organizational and management practices, increase the social safety of employees, and reduce environmental consequences [9]. These concepts often rely on the implementation of technical factors [23]. The efficiency of production and the quality of products and services relating to technical aspects in the scope of the maintenance management of a system include the safety of employees and the working environment, as well as economic, logistics, legal, organizational, and management aspects [24]. Since the point of maintenance is to prolong the good performance of equipment, the sustainability concept challenges environmentally benign processes to achieve the lean management of the production process [9]. The authors of [25] approached this issue by developing a conceptual framework for sustainability and lean maintenance in Malaysian SMEs. They highlighted the requirement for collaborative resolution and the optimization of multiple aspects of maintenance management. Thus, in this study, sustainable maintenance was portrayed as a necessary function that will become the key pillar of sustainable production by ensuring availability, improving reliability in terms of technical aspects, and improving sustainability factors to ensure the multi-dimensional safety of assets in order to achieve a competitive industry.

### 2.2. Benefits of Sustainable Maintenance for Offshore Platforms

Studies conducted on integrating sustainable maintenance with performance have established the importance of maintenance in improving the performance of an asset and achieving sustainable competitive advantages [23]. Regarding the impact of sustainability on business practices, Yusuf et al. [26] indicated that 80% of operators have already adopted measures to support sustainability in the UK O&G industry. Furthermore, the authors of [5] observed that the maintenance function in the O&G industry influences economic, environmental, and social performance in their conceptual study. This study conducted a conceptual review, integrating sustainability with manufacturing practices, performance, and maintenance, revealing the impact of sustainable maintenance in the O&G industry. Therefore, it can be seen that sustainable maintenance is essential for production and drilling corporations due to the sustainability requirements of control and decision making.

Since the contribution of maintenance is well known, attention should be drawn to the holistic concept of sustainability as a driver of performance in the O&G industry. It is anticipated that sustainability will benefit the O&G industry in the transition towards a sustainable economy [3]. Meanwhile, in their strategic focus on reducing costs and increasing productivity, the Asset Management ISO standards integrate maintenance with the concepts of production and logistics in order to gain a competitive advantage in a challenging environment [27]. Sustainable maintenance will boost entities' ability to achieve this objective by adopting performance indicators to measure the impacts of time losses and waste during production. The authors of [3] supported the notion that sustainability contributes to controlling socio-environmental risk in the O&G industry, helping entities to elude unfortunate consequences. It was further stated that carrying out competence assessments with technical knowledge is important when assessing the quality of sustainability practices [28]. Thus, the study aimed to develop indicators for implementing the TBL, including economic, environmental, and social performance components [13]. This should allow us to improve sustainable production and maintenance processes. Maintenance efficiency depends on directly improving the implementation of processes and indirectly improving the production performance and overall quality [7]. Therefore, it is necessary to establish a sustainable maintenance index through a combination of various performance indicators. Thus, a sustainable assessment should encourage entities in the O&G industry to support the implementation of actions aiming at communities and businesses [3].

### 2.3. Performance Measurement for Sustainable Maintenance

The authors of [29] explained performance measurement for maintenance as a measuring process involving different disciplines to justify maintenance investment as well as create strategic objectives for the overall industry. Maintenance managers have to contend with convoluted tasks relating to entrenching maintenance performance measures to achieve business objectives, create strategies, and influence the process and system [30]. Thus, performance measurement reflects the need to increase stakeholders' awareness of production plants by delivering a comprehensive assessment of the repercussions of carrying out maintenance as well as the sustainable objectives that have emerged from the maintenance process [7]. The maintenance performance definition provided by [31] involves aiming to minimize maintenance costs by evaluating and maximizing the overall maintenance performance. Sustainable maintenance involves economic benefits for the industry though providing an improved description of maintenance management and relevant standards [20]. Since technical and financial impacts have already been implemented to evaluate the performance of offshore process installations, a sustainability impact assessment considering the TBL approach is required. This is in line with the assertion made by [12,22] regarding the need to integrate TBL considering availability, assessing efficiency and effectiveness, and considering the consequences of not carrying out maintenance. The authors also stated that the major reasons for the coherence across multiple decision levels relate to economic, social, and environmental concerns. Sustainable maintenance performance measurement helps decision-makers to compare the effects of improved processes

and achieve sustainable performance, which will consequently foster competitiveness [13]. Finally, performance measurement for sustainable maintenance provides a view that, apart from the TBL raised in the literature, there is a need to assess relevance and efficiency while anticipating the consequences of maintenance and simultaneously ensuring the consistency of decision making to ensure the fulfilment of the constraints and commitments posed by regulations.

#### *2.4. Studies on Sustainable Maintenance and Its Key Performance Indicators*

The current section considers some of the ideas of previous studies, using key performance measures to gain a general perspective of sustainable production and maintenance for the O&G and the manufacturing industries. Since sustainable production is associated with sustainable maintenance and performance, it is important to gain insights and investigate measures relating to sustainable production and sustainable maintenance practices in other industries. The reviewed papers concern previous investigations of sustainable maintenance, especially in the manufacturing industry [7]. Others have looked at the potential environmental and social implications of the O&G industry's production performance. Studies relating to performance measures, areas, and metrics are devoted to assessing sustainability in the O&G industry by taking into account the TBL to minimize the complexity, leanness, and agility within the corporation as well as the factors influencing the supply chain outside of the corporation [3,13]. However, studies on the performance measurement of sustainable maintenance in O&G offshore platforms are not available. Thereafter, inferences will relate to proposing a comprehensive set of performance measures for the sustainable maintenance of O&G offshore platforms.

The authors of [31] discussed companies' acceptance of maintenance performance assessment, based on numerous studies focusing on performance assessment in the manufacturing industry aiming to guarantee the competitiveness and sustainability of industries. Only a few studies have depicted sustainability-related measurements with the following aspects: measures that are insufficient to address social and environmental impacts [12], including the influence of systems, related methods, and databases for lifespan evaluations for assessing sustainability on the environment [22], and sustainability issues integrated with an overall effectiveness evaluation [20]. Others have proposed frameworks for measuring maintenance impacts. For instance, the authors of [12] integrated three sustainability dimensions at the corporate, tactical, and functional levels. Additionally, the authors of [11] integrated these into a conventional maintenance management system, and [7] stated the need for the measurement of the indirect impact of maintenance processes.

Due to the environmental consequences associated with production in capital-intensive industries, operations management has expanded such metrics and measures. As reported by [15], the field of sustainability analysis of offshore O&G companies and service providers is dominated by environmental, social, and economic performance sustainability issues at a corporate level. Thus, this study highlighted the shortcomings of a sustainability report regarding the elaboration at the level of the industry's operating units. An analysis of sustainability indices in the O&G industry investigated the issue through three major dimensions at both the individual company (micro) and whole sector (macro) decision-making levels [3]. Therefore, it is necessary to review the existing literature using an integrative approach, taking into account the technical dimensions of sustainable maintenance and production in order to measure the direct and indirect impacts on performance. The measures which have been considered in the literature were characterized as generic. This is because they are considered as areas influencing the further development of specific metrics that are suitable for flexible corporations that operate offshore. Given this, the paper attempted to synthesize comprehensive measures aggregated from economic, social, environmental, and technical performance measures used for maintenance processes for production and offshore drilling equipment.

#### 2.4.1. Assessing Sustainability in the O&G Industry

The first study considered here is [26], which is a research paper that focused on the influence of green and sustainable practices on the UK O&G industry. It revealed the high level of commitment of industrial practitioners to adopting sustainability through the petrochemical supply chain and discussed the benefits of implementing sustainability measures. Additionally, the study of [32] illustrates the connection within an agile supply chain with competitive objectives, as well as business performance in the upstream industry.

Another study on the sustainable performance of the O&G industry conducted by [3] indicates the need for further investigations due to the limitations of the research work carried out on analysis and sustainability so far. The author proposed the use of a sustainability framework that incorporates TBL from the core to the outer level of the O&G industrial sphere. The resulting sustainability index considers integrating practical and productive measures with actual operations in the industry.

Further, some sustainability measures were proposed by [13], who examined the scale of evaluation of sustainability in the O&G industry with respect to environmental pollution and social damage. The analytical hierarchy process proposes the use of 19 key performance indicators for evaluating the sustainability of production in terms of the three aspects of TBL. This paper concluded that the achievement of higher performance through sustainable objectives would have an impact on increasing the competitiveness of the industry.

Another study conducted on an offshore drilling platform by [33] indicated the limitations of conventional drilling due to the complexities of environmental characteristics as well as the remoteness of the platform's locations. The authors of [14] proposed the use of a comprehensive assessment process for jack-up drilling platforms as a contribution to the green concept of offshore installations. The developed index includes advanced procedures, a rational economy, and an environmental coordinator. The method proposed considers the personal interests of stakeholders and the need for decision-makers to contribute to achieving low-carbon technology on offshore platforms.

#### 2.4.2. Maintenance Management on Offshore Installations

The maintenance performance measurement system proposed by [34] supports decision making by utilizing a restricted and comprehensive list of maintenance key performance indicators. The study was designed based on the needs of a maintenance manager's board and technicians, considering the necessary levels of effectiveness and efficiency for maintenance processes. A study on safety systems [35] and the life extension of industrial assets specified that there were benefits for economic, social, technical, and environmental performance. Additionally, highlighting the limitations of maintenance decision-making models in addressing either technical or financial issues requires the use of an integrative approach. The gap caused by not measuring the social dimensions of workforce contributions and technological investment for automation and control systems also needs to be addressed.

Thus, this study proposed a framework for the maintenance management of a drilling and production platform considering eight factors influencing safety incidents and financial losses in the O&G production process. As a result, there is still considerable ambiguity regarding conventional practices, while recently introduced maintenance methods and practices used in the O&G industry lack holistic maintenance functions to improve integrity and efficiency regarding the performance of the production system [36].

#### 2.4.3. Sustainable Maintenance as a Moderating Performance

Another study that evaluated sustainable maintenance as a performance contributor in the O&G industry [5] indicated the positive association of maintenance, social, environmental, and economic dimensions relating to the sustainable multi-attribute theory. This study revealed the demand for O&G firms to educate key personnel to improve the effectiveness of operations management. A similar conclusion was presented by [7], who studied the maintenance selection approach in order to evaluate the impact of sustainability

on manufacturing. Maintenance workforce training is prioritized as an optimal strategy for maintaining a sustainable system. Supplementary findings indicate the need for further studies to be carried out in this area that incorporate the technical dimension to define the impact of equipment performance on overall sustainability.

Many papers have proposed the use of sustainable maintenance performance assessment within the manufacturing industry. A recent review of sustainable maintenance performance measures [12] found that the manufacturing industries in Malaysia consider the social factor to be most important, followed by economic and then environmental factors. Authors of this paper believe this may be due to the absence of integration of maintenance objectives with the company's economic strategy. The authors of [20] advocated the need to achieve a higher effectiveness through selecting the right dimensions and not being limited to the overall effectiveness approach. The authors of [22] integrated TBL in a maintenance dashboard by considering availability, assessing efficiency and effectiveness, and including the consequence factor of maintenance. The authors of [7] provided a systematic literature review to propose a framework for measuring the influence of maintenance on the TBL. They did not include the technical dimension, as this is already in use in the manufacturing industry. Derived from the literature on sustainability within the O&G industry, it is concluded that maintenance has not been considered as a performance driver for overall competitiveness.

In summary, the authors of [5] highlighted the following requirements as a sustainability perspective for the O&G industry. Firstly, sustainability dimensions are limited to TBL. Some studies include socio-economic dimensions; however, their integrated overall efficiency and effectiveness is limited. In addition, it is also important to consider the broadening dimension of environmental consequences apart from the limited impact of social health and safety [35], as well as the necessity of the development of a framework for assessing sustainability from a maintenance perspective for O&G offshore installations. Maintenance performance measurement frameworks are generic and are not customized based on the industrial context [34]. Finally, it is important to include the effect of performance assessment indicators for sustainability on the production and maintenance of offshore installations.

### 3. Maintenance of Oil and Gas Offshore Platforms

Due to the corporate modification of maintenance function and the advancing complexity of production and drilling technologies, hazardous industries such as the O&G industry require a shift to adapting the changing dynamic of a competitive environment. According to [10], maintenance comprises a consequential support function in industry through securing investment in physical assets and targeting organizational goals. The technological advancement employed on offshore installations entails new challenges in terms of planning and measuring production managing wells, subsea system, production, and transportation [2]. Thus, the sector is experiencing persistent maintenance challenges due to the complexities of incorporating advanced technologies into maintenance strategies offshore [36]. Apart from the integrated new technologies and the technically challenging fields, demands for efficiency and complexity in production due to the remote areas of work, the offshore environment is believed to be potentially hazardous, dangerous, and socially isolating [17]. These hazards posed to personnel make it necessary to consider the human factor for the improvement of operability and maintainability [37].

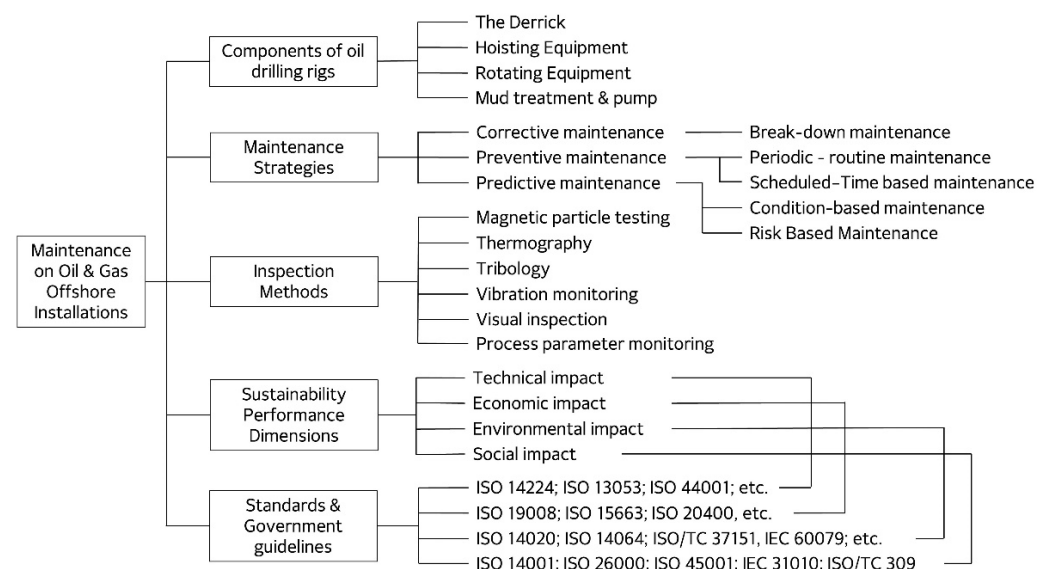
To consider the outcome of maintenance activities and breakdowns in O&G industry corporations, the authors of [38] highlighted the effects of pollution, injuries, and waste of energy and resources. Decision making regarding sustainable equipment maintenance in an offshore oil and gas platform is a complex process involving the analysis of multiple objectives based on complex and multi-faceted criteria covering quality, safety, and the environment [39]. These factors are responsible for performance and necessitate many general metrics to fit the maintenance processes of O&G offshore installations. Thus, the

implementation of sustainable maintenance performance measurement is important in order to ensure the O&G industry's environmental, economic, and social sustainability [5].

### 3.1. Production and Drilling Equipment Maintenance on Jack-Up Offshore Platforms

Invented for the exploration and production of oil and gas, jack-up structures comprise 41% of mobile offshore structures [40]. The importance of jack-ups for sustainability is highlighted from the traditional emphasis of technical advancement and economic rationality as the offshore drilling structure. The further incorporated "Green" concept or GJDP [14] proposes environmental coordination in the phases of design, construction, service, and deconstruction. Therefore, there is a high requirement for maintenance decision-making strategies to meet challenging sustainability dimensions for drilling and production equipment on offshore installations.

Maintenance on offshore installations, compared with other industries, includes a variety of unique characteristics in terms of scope and complexity (Figure 1). The jack-up drilling components consist of a derrick, hoisting equipment, rotating equipment, and mud-treatment equipment. Referring to related literature, the maintenance decision-making logic implemented on these components includes Reliability Centered Maintenance (RCM), which implements failure and effect analysis for prioritizing safety-critical equipment, and Total Quality Maintenance (TQM), which implements lean understanding into maintenance for the availability and productivity of the system. Then, based on the outcome of the decisions, the following strategies are assigned: lubrication (LUB), service (SVC), corrective maintenance (CM) identified as a failure-responsive approach, preventive maintenance (PM) scheduled by the reliability metrics of materials and historical data of failure (time-based maintenance TBM), predictive maintenance (PdM) approaches incorporating the condition of equipment based on inspection and monitoring of hidden failure detection (HFD), and condition-based maintenance (CBM) [5,39].



**Figure 1.** A framework used to classify the literature on the maintenance of O&G offshore installations.

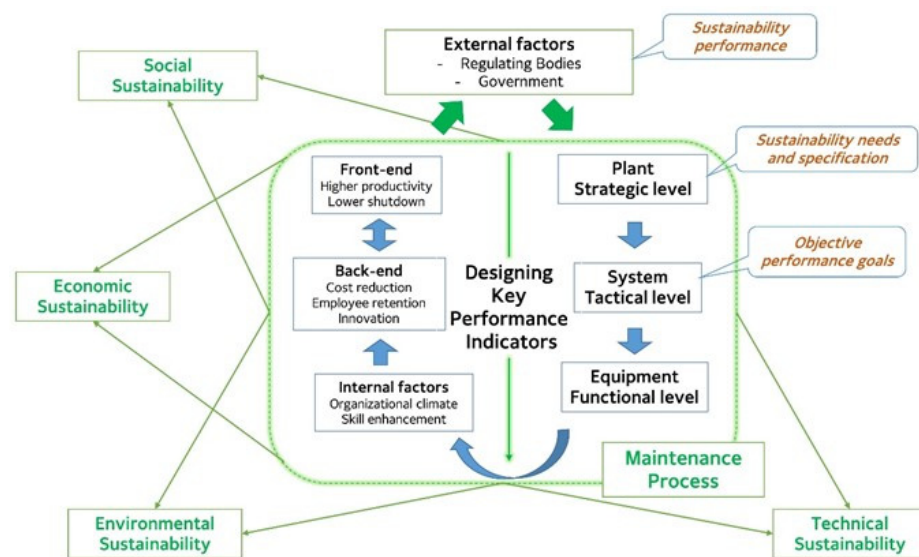
### 3.2. Sustainable Maintenance Framework for Performance Evaluation

Maintenance performance measurement is a multidisciplinary process used for assessing maintenance and considering stockholder requirements from a general industry perspective [29]. Due to the significant impact of the O&G industry on sustainable development [13], the assessment of production and maintenance performance necessitates that decision-makers consider both the overall efficiency of the organization [41] and the adverse impact on the surrounding area [13]. On the other hand, the social investment and satisfaction at the multilevel side of the plant are important [12], as the authors of [26]



indicated the requirement for cooperation between governments, businesses, individuals, and multi-lateral institutions to enrich sustainability. Additionally, the essence of the human factor is a contributor to the availability and productivity of any system [36]. While assessing maintenance performance is necessary in strategic decision making, [5] management needs to gain an understanding of balanced sustainable performance and sustainable maintenance through a measurement framework ensuring consistency within decision levels assessing the balance of dimensions in maintenance performance.

In the light of these sustainability objectives for maintenance management, a framework for measuring its performance using sustainability dimensions is necessary. It is on that basis that a framework which undertakes a sustainability objective was proposed, as presented in Figure 2. To overcome the impact of maintenance on various sectors of the plant, a framework for maintenance decision making relating to the hierarchical levels of an organization considering the four proposed dimensions of sustainability was implemented.



**Figure 2.** Sustainable maintenance performance assessment framework.

Initially, sustainability specifications are delivered by stakeholders. There are other influential factors on the plant level of the production and drilling platform. For the successful incorporation of sustainable maintenance, the strategic level requires us to define the organizational expectations and requirements for sustainability compliance. Thus, plant issues on the perceptual measures from stakeholders are linked to the long-term subjective goals.

Through decreasing subjectivity, the tactical level is challenged with specific issues of processes for sustainability compliance assurance. The objectives need to cascade into a cluster of individual objectives [42]. Thus, these include engineering strategies, modifications of processes for less pollution and waste; diminishing the requirements of energy and material resources; and the consistent espousal of guidelines, metrics, and tools for sustainable design. In this way, system performance within sustainable objectives and performance goals for the strategic level are evaluated through the impact of maintenance on a tactical level, while considering the overall influence of sustainable dimensions of the maintenance process.

The objective level or the functional level is responsible for the preparation and prioritization of action plan and implementation processes. Thus, a sustainable maintenance performance measurement framework is needed in order to link to the hierarchical levels for effective management. This ensures that those objectives derived from stakeholders' requirement are considered for effectiveness for front-end and back-end processes involving employees at various decision-making levels of an offshore installation.

Defining measures for the monitoring and control of management decisions implies complexity due to multi objectiveness of sustainability dimensions. The maintenance performance measurement framework will provide a solution to this by linking with organizational strategy and considering the four dimensions of sustainable maintenance measures. The technical dimension will be concerned with the equipment maintenance performance measures at the tactical and operational levels of the equipment that impact the system. Simultaneously, this will help to maintain the integrity of the TBL terms of sustainability. Then, it will be incorporated into the maintenance process of the plant as being addressed to an economic, social, and environmental performance that strives to effect sustainable performance. The explanation for this is supported the definition by [7], which states that sustainable maintenance should address the direct and indirect impact of the maintenance processes of an organization.

### 3.3. Key Performance Measures

These were a set of reference conditions adopted to compare “distance of target” or the difference in the current and desired situation aggregated from functional (shop floor) level to higher, managerial level [31]. In accordance with priorities or standards, performance indicators differ among companies and industries. The author of [43] defined performance measures as properly utilized opportunities for the improvement of the organization. Thus, maintenance performance indicators are quantifiers developed for measuring the productivity of maintenance processes. The distinction of maintenance performance indicators in production and drilling plants might not be excessive, as it concerns strategic, tactical, and operational planning, including the function of the evaluation of the performance of actions in maintenance decision-making management [31]. One cluster of indicators is inadequate, concerning the capability of considering multiple aspects for financial reports, monitoring employee satisfaction as well as overall equipment effectiveness. The authors of [44] proposed evaluating sustainability by bringing innovative practices to conventional maintenance decision making to achieve sustainable objectives of the industry. In support of this, the author of [45] stated the necessity, apart from focusing on the technical dimension of maintenance, to consider as an incorporated cluster with socio-economic and environmental safety dimensions. To buttress this further, it was pointed out that the four dimensions, involving technical, economic, social, and environmental safety in maintenance, were rarely considered in the literature [20]. In summary, apart from the TBL discussed in the literature, there is a need to assess relevance and efficiency while anticipating maintenance impacts and simultaneously securing the conformity of decision-making levels and reflection on the corporation’s strategic objective.

#### 3.3.1. Technical Sustainability

This takes the structure of traditional metrics of maintenance performance: that the major objectives are to ensure overall equipment effectiveness. From the maintenance perspective, asset management should comprise technical conditions in integrated planning for operational, tactical, and strategic decisions [46]. The performance measurement in this dimension includes the effectiveness of maintenance actions, namely, quantifying influence on reliability, availability, and maintainability of equipment for the sustainability of maintenance process at the strategic level of plant integrity. Consequently, the performance indicators presume approaching comprehensive assessment standards implemented in the offshore installation in order to make sure to contribute to the production and drilling offshore.

#### 3.3.2. Economic Sustainability

This concerns the outcome of the interaction between social factors and the environment, which contributes to the extensive endurance and economic efficiency of an organization [26], unless the key objectives strive to the ensure utilization of resources in an efficient way for effectiveness, considering the constraints of resource exploitation. Under

the economic sustainability in the O&G industry, the area of focus is finance, work force, and code of conduct and legibility [3] merged into a sustainability understanding of the impact on the local community for resource efficiency and production methods with a waste disposal strategy. Hence, the performance indicators of this dimension require the assessment of maintenance impact areas by the use of cross-sectional coordination between multiple departments.

### 3.3.3. Environmental Sustainability

Under this dimension, maintaining natural resources without creating extensive waste cannot be accommodated by nature. The issue of depletion of oil reserves and limits of renewability requires thoughtful exploitation and pollution as a threat to self-restock of these sources [26]. The environmental challenges faced by the O&G industry cause it to implement new efficient and economic approaches for environment perspective. To reach such objectives, the authors of [3] suggested to consider the impact of waste on quality of water and air that measured by an offshore waste management plan, including the requirement of drilling activities' impact on the surrounding environment through undesirable atmospheric emissions. Since many efforts are devoted to minimizing the environmental impact of production and drilling processes of O&G companies that are operated offshore, the maintenance of those installations and equipment necessitates the sustainability concern of oil spills, environmental regulations, and resource savings.

### 3.3.4. Social Sustainability

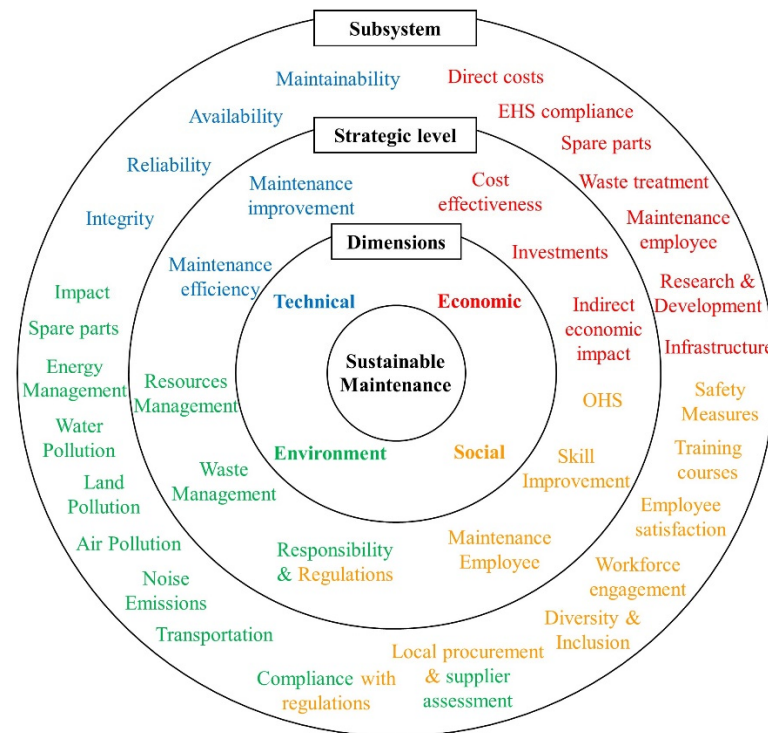
From the perspective of social sustainability, the WCED reported it as a concept of "needs", emphasizing the human aspiration and needs [26]. This concerns the requirement of maintaining people's quality of life without harming the environment and overexploiting the limited resources as an extension of environmental links. Additionally, ensuring the political and economic rights of communities through the major objectives of this will be to develop socially conscious incorporation for sustainable human development, thus, enabling different social actors to interact efficiently through encouraging cooperation of institutions. In the case of the O&G industry, the perception of "needs" were maintaining the social status of the community by providing health, safety, social equity, and the security to satisfy and fulfil the community. Therefore, the sustainability performance measurement of this dimension involves knowledge, skills, and abilities as performance criteria of the labor market for the economic dimension [44]. Consequently, the performance indicators will support decision making for accessing the social investments to endorse community.

## 4. Key Performance Measures for O&G Offshore Installations

Four generic dimensions were presented in accordance with the indicators identified by researchers and classified into sub-categories of decision-making levels. In conformity with the establishment from the literature, the classification was based on the sustainable maintenance measurement dimensions, illustrated in Table A1 (In Appendix A). Thus, comprehension with the reviewed literature indicates the significance of the dimension evaluated through a facility against sustainable maintenance management. Figure 3 illustrates color-based presentation of four-dimensions of sustainability for 12 strategic indicators and associated tactical-functional level sub-indicators entitled as "Subsystem".

From Figure 3, it can be observed that the technical dimension is categorized into the (1) Maintenance improvement and (2) Maintenance efficiency of maintenance at a strategic level of the plant. The quality of maintenance concerns the effectiveness of overall plant, namely aiming at highlighting the influence on equipment reliability, availability, and maintainability on a functional level that reflect department effectiveness on a tactical level of the system [12]. Here, reliability is defined as system to operate at desired rate under stated operating conditions for a given period [47]. Availability is characterized as a function of being uninterrupted without any problem [47]. Maintainability is proposed as an ability of the system to be restored to the necessary condition indicated by location

for maintenance, accessibility, maintenance procedures, and resources [47]. On the other hand, Maintenance efficiency evaluates maintenance program achievement. This study suggests Maintenance efficiency as an individual factor or as a productive perspective that is attributed to effective preventive, predictive, or emergent maintenance/replacement activities and integrity that impact task assignment at the tactical decision-making level [12]. Furthermore, with the enhancement of sensor technologies and growing ubiquitous availability of data, the authors of [48] defined it as the integrity of condition monitoring for improved management in management applications.



**Figure 3.** Conceptual indicators for the sustainable maintenance framework.

The environmental dimensions presented in Figure 3 include (3) Management of resources, (4) Waste management, and (5) Responsibility and Regulations. First, the dimension of Management of resources corresponds to a set of tactical level measures [12], such as the efficient management of spare parts categorized by recycling parts for maintenance processes and the amount of materials used for that [7]. This also covers the consumption of lubricants according to the amount of persistent, bio-accumulative, and toxic chemicals that are utilized for services [7]. Furthermore, the consumption of water resources and the energy management employed within and outside of the organization was evaluated [7]. Second, Waste management refers to the bio-degradable components of maintenance processes that require adequate responses to water, land, and air pollution; noise emissions; and extra transportation for waste caused by maintenance processes at the tactical and functional levels of decision making [12]. Third, the dimension of Responsibility and Regulations was divided into three categories: compliance with regulations, supplier environmental assessment, and environmental non-conformities. Compliance with regulations is associated with legislation relating to environmentally sustainable production driven by government regulations, knowledge infusion, and institutional pressures from foreign competitors [7,26]. Environmental non-conformities are imposed as complexities associated with the harsh operating environment and monitoring of offshore platforms [39].

The economic dimension of sustainable maintenance describes the efficiency and effectiveness of maintenance management with regard to corporate financial performance [44]. It has been suggested that economic measures should cover both financial efficiency and

the extended impact of the economic system of the corporation. Therefore, the economic dimension for maintenance management in the O&G industry was divided into three conceptual strategic-level indicators, namely, (6) Cost-effectiveness, (7) Investments, and (8) Indirect economic impact. First, Cost-effectiveness refers to the direct cost of actions relating to preventive and corrective maintenance policies and financial losses regarding environmentally benign production and waste management strategies [12]. Measured by the value of maintenance waste treatment, it is thought to contribute to increasing profits [48]. Second, Investments was identified as the evaluation of funds used for research and development aimed at advancing technological infrastructure and services. Thus, it is measured by investments in scientific research and experimental development for maintenance-oriented technological innovations [7]. This dimension aims to increase the use of energy-efficient equipment and the investments dedicated to related initiatives. Moreover, there are measures related to investments in the development of infrastructure and services within plants [7]. In addition, corporation investment policies contribute to local procurement, such as by hiring a local labor force and preferentially using local service suppliers are included. Third, the dimension Indirect economic impacts refers to the indirect economic impact of maintenance, which is exemplified by the non-compliance of the targeted system's performance and equipment failures influencing the production process [7]. Hence, this dimension is measured by financial losses associated with the waste of energy resources utilized for maintenance processes. Operations relating to the storage, purchase, and recycling of spare parts and tools, such as waste electric and electronic equipment were considered [7].

The idea of "Putting people first" highlights the centrality of society in political and investment programs that aims to address the requirement of cooperation between governments, businesses, individuals, and multi-lateral institutions [26]. The requirement for clarity and consistency in social performance measures aiming to address the evolving interest in sustainability reporting in the O&G industry was highlighted. This study addressed conceptual strategic-level measures incorporated into the social sustainability of maintenance management involving the dimensions of (9) Skill improvement, (10) Occupational Health and Safety, (11) Maintenance Employee, and (12) Responsibility and Regulations. First, Skill improvement relates to the learning and growth of maintenance employees from the perspective of sustainable maintenance and relevant initiatives [12]. These initiatives aim to increase operators' awareness of equipment and new procedures and fix incorrect installation practices that have consequences for social and economic safety [7]. Thus, there are skill management programs dedicated to cognitive ergonomics, risk-control programs for managing stress in complex procedures, experience and training, fitness for duty, counselling workforce, and family members in the event of serious diseases [7]. Second, the Occupational Health and Safety dimension refers to the provision of OHS due to the influence on labor caused by injuries and the impact on the physical working environment [12]. Safety measures include the use of personnel protective equipment, and the number of measures implemented for maintenance processes, as well as initiatives for fail-safe equipment suggested in maintenance employee feedback [7,44]. Another concern is lost time, as well as health and safety problems among maintenance employees related to their occupation [7,44]. Third, the dimension of Maintenance Employee was divided into three categories: Employee satisfaction, Workforce diversity and inclusion, and Workforce engagement. Employee satisfaction is associated with the value of society. It is an indicator that is evaluated by complaints from operators and engineers performing maintenance activities [12]. Workforce diversity and inclusion relates to diversity, which concerns equal opportunities being given to female workers and racial minorities [7]. Workforce engagement refers to the contribution of personnel to services and innovative approaches for sustainable maintenance [12]. From a practical perspective, this measure focuses on labor hours in corrective and preventive services [7]. Fourth, Responsibility and Regulations was divided into two categories: Local procurement and supplier development and Compliance with regulations. Local procurement and supplier development concerns the focus

of the industry on the local community, which includes benefits for labor through hiring a local workforce and assessing suppliers based on the social dimension [7]. The local community refers to the social institutions integrated with the business objectives of a corporation. Compliance with regulations is associated with sanctions under the guidance of government regulations, including knowledge infusion and institutional pressures [26] for maintenance management within a social and economic area [7].

As reflected in Figure 3, this study incorporated conventional indicators and instituted new ones to provide a class of extensive key performance indicators for sustainable maintenance in O&G offshore installations. The proposed design retains measurement areas classified into technical, economic, environmental, and social dimensions to make assessment easier.

#### *Discussions and Implications*

A sustainability assessment method that classifies maintenance performance into four dimensions for the O&G industry was proposed. These include technical, economic, environmental, and social sustainability dimensions. Additionally, a cluster of key performance measures was developed based on the proposed framework.

The rationale behind this framework is that using a maintenance decision-making process for the performance of an entire plant makes the assessment cumbersome and inefficient for the organization. The study employed diverse impact factors to help create balance for the overall process; however, it implies different initial objectives. First, on the premise of meeting the industry's standards and maintenance features, production and drilling equipment maintenance were considered according to the overall effectiveness. As such, the sustainability of maintenance processes might not be accomplished by utilizing one dimension alone [5,12,39].

On the other hand, the study used multiple dimensions based on the organizational objectives of the industry. The competitive environment of this capital-intensive industry requires corporations to consider environmental and social dimensions as equal to the economic performance of the production, suggesting that achieving a sustainable maintenance process is unattainable in isolation from these measures. Additionally, it is deemed that the proposed framework will encourage decision-makers to reconsider maintenance performance measurements for sustainability, as the maintenance will be more integrated. Thus, the study aligns traditional maintenance management and sustainable maintenance performance in the O&G industry.

The second issue that needs to be addressed is that, in order to achieve comprehensive sustainable maintenance, especially for the O&G industry, a more detailed list of factors should be utilized [3]. Due to the limited interpretations of environmental consequences presented in the literature, which often only address the impact of social health and safety, the proposed framework illustrated an expanded dimension of performance measurement. This framework enables a broad approach to be taken to of integrative impact areas, enabling the convenient interpretation of the measurement results based on the sustainable objectives of performance measurement. However, further challenges such as technological advancements and the necessity of the education and training of personnel are important measures that necessitate performance enhancement. It is on this note that the influence of maintenance on performance proven by the literature requires us to consider the consistency of these dimensions to evaluate the overall performance or enrich sustainability by enhancing the maintenance process.

The proposed framework has potential theoretical and practical uses for sustainable maintenance performance measurement. Thus, it is a contribution to analyses of performance dimensions through a framework developed to improve the assessment of offshore production and drilling maintenance. It can also be applied in the establishment of a sustainable maintenance performance measurement procedure for O&G facilities. From this perspective, the proposed framework will enable researchers to create guidance for balancing the sustainable performance dimension of other plants, located onshore and offshore within the industry.

It is also should be emphasized that integrating traditional maintenance measures and competitive performance measures will promote environmental and social concerns simultaneously while retaining an economically attainable production and drilling process. This will consequently assist in the achievement of numerous environmental and social regulations, help introduce a trustworthy business image, and increase profits. This is a response to stakeholder requirements and will help to increase multi-institutional collaboration. Sustainable maintenance could help the industry to reach its objectives by applying the proposed framework and the performance indicators in decision-making processes.

## 5. Conclusions

Through a literature review on the analysis of maintenance processes within the O&G industry, this study proposed an approach for the performance assessment of production and drilling offshore installations. In this research, performance measurement for sustainable maintenance in the O&G industry using a sustainable approach was discussed. In conclusion, this study suggests the use of a four-dimensional evaluation of performance measures integrated into the decision-making process at the strategical, tactical, and functional levels, concerning technical performance and environmental, social, and economic sustainability. In accordance with the rationale that was previously discussed, it is anticipated that the proposed framework will be of theoretical and practical use, improving the efficiency and effectiveness of maintenance processes by meeting the sustainability objectives of an O&G offshore installation. Consequently, it could help regulatory bodies to assess the performance of installations in reaching the objectives of sustainable development. These may include aspects such as cost-effectiveness, lowering carbon emissions, the utilization of resources, and social fairness. It is recommended to apply this framework against the traditional maintenance method and establish a comparison by making inferences to analyze the efficacy of the approach. Another suggestion is to expand the framework to help it align with the concept of Industry 4.0 and to evaluate the technological point of view of maintenance performance measures for other offshore installations. Finally, the authors of this study recommend developing suitable metrics for the assessment of sustainable maintenance performance in accordance with the key performance indicators relevant to the proposed framework.

This study is not exempt from several limitations, which create the opportunity for further investigation. First, in view of the performance indicators, there is a need to evaluate their significance in terms of importance and applicability within the O&G industry. In the next study, we intend to pursue this objective and conduct expert consultation to validate the proposed framework. Second, this study focused on conceptual indicators at a strategic decision-making level and their subordinate measures at tactical or functional levels. This limitation presents an opportunity to study the association of these indicators, specifically the functional-level indicators, with maintenance decision-making models, such as the overall equipment effectiveness (OEE) [49], failure mode and effect analysis (FMEA) [50], and quality function deployment (QFD) [51] models. Third, the conceptual framework was dedicated to the operation of offshore platforms. Since the natures of these operations are not similar, scholars are encouraged to extend this concept to assessing the impact of upstream and downstream operations, as well as the influence of third-party companies where maintenance operations are performed by contractors. Fourth, this study focused on evaluating four-dimensional sustainability as a framework for the maintenance of normal conditions (mandatory shutdown). Hence, the study did not consider breakdowns or emergency maintenance due to accidental spillages, gas releases, fires, or explosions. The proposed framework deserves further improvement, yet this paper mostly aimed to spark interest in the emerging concept of sustainable maintenance among researchers and practitioners.

**Author Contributions:** Conceptualization, E.U.O. and K.Y.W.; writing—original draft preparation, Y.D.M.; writing—review and editing, J.Y.C.E. and K.Y.W.; visualization, Y.D.M.; supervision, E.U.O.; funding acquisition, E.U.O. and K.Y.W. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by UCSI University through the Pioneer Scientist Incentive Fund (PSIF), grant number Proj-In-FETBE-062. It was also supported by Universiti Teknologi Malaysia (UTM) (Vote Number: 20H69).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data presented in this study are available in Appendix A.

**Acknowledgments:** The authors wish to express their gratitude to the reviewers for their constructive comments that helped us to significantly improve this study.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Appendix A

**Table A1.** Conceptual indicators with thematic references for the Sustainable Development Goals and the Global Reporting Initiative.

Strategic Indicators	Tactical Indicators	References	Thematic References for SDG & GRI
1. Maintenance Improvement	Reliability	[2,47]	-
	Availability	[47,52]	-
	Maintainability	[47]	-
2. Maintenance Efficiency	Integrity	[53,54]	API RP 750
3. Management of Resources	Energy Management	[55,56]	Energy: GRI 302-1,3,4; API ENV-5. SDG-7, SDG-8, SDG-12, SDG-13
	Impact	[9,55]	Products and Services Responsibility: GRI-OG8; API ENV-5, ENV-A7-8; SDG-12, SDG-13, SDG-14, SDG-15
	Spare parts	[55,57]	API ENV-A5
4. Waste Management	General	[13,55,56,58]	Waste and effluents: Environmental Quality Regulations 2009; GRI 306-2,3 OG7; API ENV-A1-4; SDG-3,6,12,14.
	Water pollution	[13,55,56]	Water: GRI 303-1, 5; API ENV-2; SDG-6, 8, 12.
	Land pollution	[54,55]	Biodiversity: GRI-OG 4; API ENV-A.9; SDG-12, 14, 15.
	Air pollution	[13,55,56]	Emissions: GRI 305-1,2,3,7. API ENV-3, ENV-A6. Environmental Quality Regulations 2014. SDG-12-15.
	Noise emissions Transportation	[7,59] [7,56]	Ergonomics. OSHA 1994 -
5. Responsibility and Regulations	Compliance with regulations	[55,56,60]	Compliance: GRI 307-1; API ENV-6. SDG-8, 12.
	Supplier environmental assessment	[7,26,61]	Supply Chain. GRI 308-1, 308-2. SDG-8, 16.
	Environmental non-conformities	[59]	Ergonomics. OSHA 1994
6. Cost-effectiveness	Direct costs	[13]	-
	EHS compliance	[7]	-
	Spare parts	[7]	-
	Waste treatment	[7]	-
	Maintenance Employee	[55]	API ECO-A2
7. Investments	Research and Development	[2,7]	Community investment.
	Infrastructure	[56]	GRI 201-1; OG2. SDG 7-9.
8. Indirect economic impacts		[2,7,56]	-
9. Skill Improvement	Training courses	[44,55]	API SOC-5
10. Occupational Health and Safety	Safety measures	[2,13,39,56,59]	OHS. Factories and Machines Act 1967. GRI 403-5; API H&S-1-5. SDG-3, SDG-8
11. Maintenance Employee	Employee satisfaction	[7,55]	API SOC-A2
	Workforce diversity and inclusion	[7,13,55]	Diversity: GRI 405-1; API SOC-4. SDG-5, 8.
	Employee turn-over rate	[7,56]	Labor practices. Employment Act 1955.
	Workforce engagement	[13]	GRI 404-1. SDG-4, SDG-5,8.
12. Responsibility and Regulations (Social)	Local procurement and supplier development	[13,20,61]	Procurement Practices: GRI-204-1; API SOC-A3; SDG-12. Supply Chain SCOR APICS; GRI 414-1,2. SDG-5,8,16.
	Compliance with regulations	[7,56]	Compliance. GRI 419-1; SDG-16



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