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Decommissioning of Offshore Platforms in Adriatic Sea: The Total Removal Option from a Life Cycle Assessment Perspective

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Abstract: The international energy scenario to date is heavily based on fossil energy sources such as coal, oil or natural gas. According to the international ecological goals of the UNFCCC formalized in the legally binding treaty called the Paris Agreement, the next global challenges will be the decommissioning, dismantling or reconversion of the current fossil energy system into a new, more sustainable system that makes more efficient use of renewable energy technologies. Worldwide, there are about 6500 offshore oil and gas facilities and about 130 of them are located in the Mediterranean basin, mainly in the Adriatic and Ionian Seas: more than 110 offshore gas platforms have been installed in these areas since 1960. In this paper, using Life Cycle Assessment, the environmental and economic impacts of the total removal operations of an existing offshore platform in the context of the Adriatic Sea are assessed based on existing and registered decommissioning projects. In addition, the avoided impacts of primary steel production due to its recovery and recycling from the removed platform are assessed using the system boundary expansion method.

Keywords: life cycle assessment; decommissioning; offshore platforms; O&G

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1. Introduction

Today, throughout the world, a fundamental structural change is taking place in the energy sector, with the transition to renewable energy sources, sustainable structures, and processes, economics, and energy policy. Precisely from the perspective of sustainable development and decarbonization, a compulsory step to achieve the celebrated socio-economic goal of zero net climate-changing gas emissions, the key points of this energy transition are being outlined, one of which is the decommissioning or, preferably, the reuse of infrastructures linked to the "old" energy system [1]. It is expected that the oil and gas (O&G) sector will be the most affected by this strategy in response to the public's perceived discontent with the long-term damage caused by the focus on short-term profits widely seen as a serious threat to marine and maritime environments [2].

Decommissioning refers to the final phase of the life cycle of assets belonging to the O&G supply chain and industrial plants in general. It is therefore to be considered a fundamental part of the investment process and can have important economic, social and environmental implications in the context in which it is carried out. Although in the past this activity had little visibility, in recent years, due also to greater general awareness, stakeholder interest has been gradually growing. Decommissioning represents an opportunity both in terms of employment and the regeneration of raw materials and/or assets that, at the end of the industrial life cycle for which they were designed, still have the possibility of being reconverted and reused—in whole or in part—for other initiatives. Decommissioning should therefore be understood as a perfect representation of the concepts of efficiency, circular economy, and sustainability, which fits perfectly into the priorities of the energy transition and Blue Economy.

The objective of the study is to highlight and assess the environmental impacts of decommissioning operations related to the total removal (a standard choice suggested by most of the attached international regulations) of a single-pipe offshore platform, "Viviana 1", through the Life Cycle Assessment methodology, regulated by the ISO 14,040 and 14,044 standards. The current literature references on offshore platforms operations focus on wind energy platforms, and the few on offshore O&G platforms refer to the North Sea context, although these are very different areas. Due to the unavailability of specific data on the "Viviana 1" platform, facilities, and technologies considered in the decommissioning program, the study had to refer to validated literature data. In Section 2 the Life Cycle Assessment methodology, the case study of "Viviana 1" and the results of the analysis for each impact category are presented. Platform "Viviana 1" is being decommissioned through total removal option that consists of the removal of the preliminary equipment, the closure of the oil well and the cleaning of the jacket cutting points; the cutting and transportation phase of the topside and jacket; the removal of the connection pipelines; the unloading on the apron; the treatment of the platform sections and the separation of materials; the recovery and recycling of materials and the disposal phase. The platform's recyclable material consists mainly of steel and iron scrap that can be processed in recycling centers and secondary steel plants to produce new recycled steel, replacing the same amount of primary steel. Lastly, in Section 3, an economic impact assessment of the total removal project as esteemed by stakeholders is provided together with a more specific description of each decommissioning project phase.

The results of this study represent a starting point for improving the efficiency and minimizing the environmental impact of the entire production system under consideration, avoiding burden-shifting, and promoting alternatives to total removal wherever possible.

2. Materials and Methods

The "Viviana 1" platform (Figure 1), owned by ENI S.p.A., is a single-pipe platform of about 20 m depth located in the Adriatic Sea, 9 km from the coast and about 20 km from the port of Pescara. I is close to the end of its productive life. The structure of the platform, inferred from the existing literature and from the decommissioning projects of similar Italian platforms [3–8], consists of a single extraction well inside which is a guide pipe that extends beyond the mud line for about 16 m. The upper part consists of a small platform for maintenance and monitoring operations; there are 13 anodes on the outer surface of the pipe and all connections with other platforms were already closed during previous end-of-life operations.

Figure 1. "Viviana 1" platform.

The LCA applied to the specific site of the "Viviana 1" platform considers the characteristic installations, technologies and sources of supply. The analysis includes the following steps:

- Definition of the Goal and Scope;
- Life Cycle Inventory;
- Life Cycle Impact Assessment;
- Life Cycle Interpretation.

Final results are presented using category indicators to aggregate all types of emissions into impact categories by applying relevant characterisation factors.

2.1. Definition of Goal and Scope

The objective of the study is to assess the environmental impacts of the cutting, transport, disposal and recycling operations associated with the total removal of the "Viviana 1" offshore platform decommissioning project. The boundaries of the system under study are illustrated in Figure 2, where the foreground and background systems are also delineated:

- The foreground system includes the processes whose choice and mode of management are directly influenced by the decisions based on the LCA study.
- The background system includes all other processes that interact with the foreground system, usually by supplying it with materials and energy or by receiving materials and energy from it.

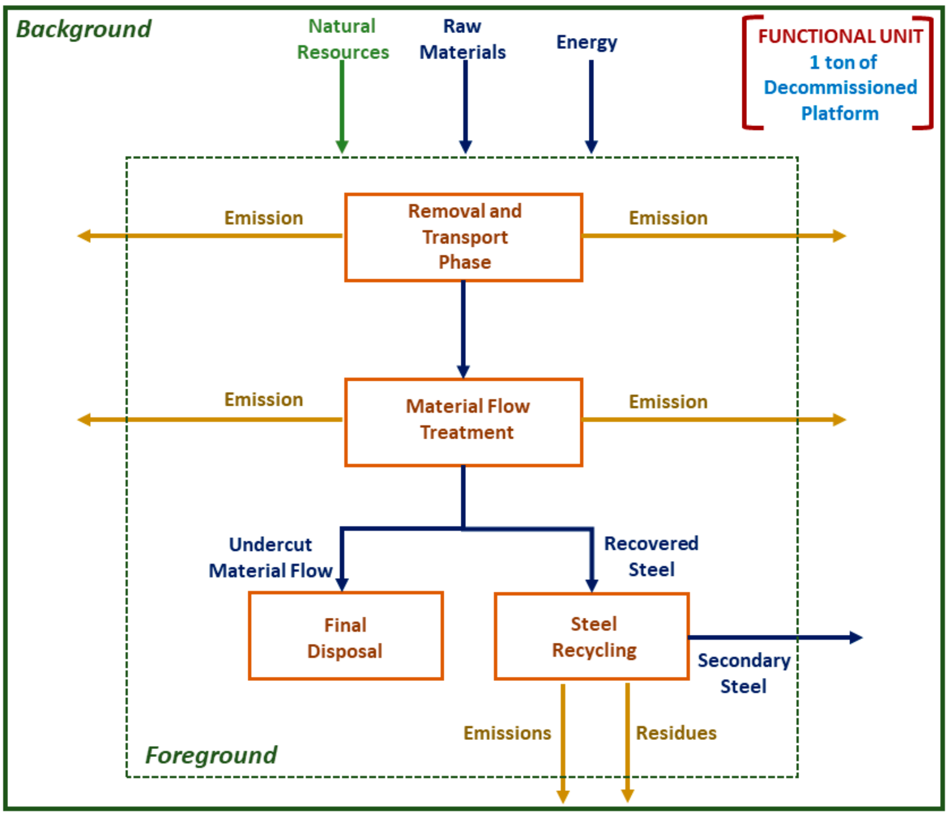


Figure 2. Background and foreground systems under study.

An essential aspect is the definition of the functional unit of the system. A collective system represents several interconnected processes flows with its subprocesses [8]. Thus, a system can be determined through its intended function. The functional unit serves as the reference unit for the system in which inputs and outputs are determined [9]. The inputs and outputs for the model are calculated using the reference flow. Comparative LCAs are modelled based on a similar function that is evaluated by the similar functional unit with corresponding reference flows [8].

The functional unit is represented by 1 tonne of decommissioned platform.

The study was conducted under the assumption that the site, the primary and secondary steel production plant, would be located near the port of Pescara and that waste other than steel would be sent for disposal.

The impacts avoided through the production of secondary steel recovered by recycling the platform's scrap are considered to support decision about the platform dismission alternatives.

The methodology used for impact analysis in the Life Cycle Impact Assessment (LCIA) phase was ILCD2011, considering the categories "Climate Change", "Human Toxicity, Cancer Effects", "Land Use", "Marine Eutrophication", "Particulate Matter", "Water Depletion" (better explained in Section 2.3). The ILCD2011 (International Reference Life Cycle Data System) impact method is the result of a project conducted by the Joint Research Centre (JRC) of the European Commission to reach consensus on the recommended method for each environmental theme by analyzing different Life Cycle Impact Assessment methodologies. For the other data, reference was made to the ELCD database [10]. The methodology used for impact analysis in the Life Cycle Impact Assessment (LCIA) phase was ILCD2011 which includes the categories "Climate Change", "Human Toxicity, Cancer Effects", "Land Use", "Marine Eutrophication", "Particulate Matter", "Water Depletion".

Multifunctionality occurs when a process unit outputs consist of multiple products (i.e., coproducts, byproducts, recirculation, etc.). This aspect raises the question of how to divide the impacts caused by the process among the different products. The ISO standards indicate that multifunctionality should be avoided, if possible, by splitting of the system into many subprocesses, each producing a single product. When the splitting is not possible, multifunctionality should be assessed by means of system expansion or allocation.

In this case, multifunctionality was considered by expanding the system. System expansion allowed to evaluate impacts linked to a specific product of a multi-output process unit by subtracting impacts connected to the uninteresting ones obtained by considering specific unit process systems or process units that are properly external to the boundaries of the study.

The study will help to identify the environmental impacts related to the selected impact categories and to identify the most important life cycle phases causing the calculated environmental impacts related to the decommissioning of the "Viviana 1" platform.

The primary data used for the foreground system were obtained by averaging the literature data with the greatest consistency with the study [11–20], while secondary data were retrieved mainly from the ELCD database.

The generated dataset of overall mass and energy input–output data can be considered representative of the European context of technology and plants [21].

A detailed description of the processes involved in the life cycle inventory and the data sources used for modelling is provided in the following paragraphs.

2.2. Life Cycle Inventory

2.2.1. Primary Steelmaking

The primary steelmaking process system consists of the following process units: coke oven, which produces the coke used in steelmaking; sinter plant, which produces the sintered iron ore; blast furnace, which produces pig iron, and basic oxygen furnace, which produces the final steel [22,23] (Figure 3).

The coke oven is a large furnace in which the pyrolysis of coal takes place at about 1200 °C, producing a solid carbonaceous material with a low sulfur and ash content called coke.

Sintering is a high-temperature process that produces a solid metal object by pressing its powder with polymeric chemical binders, such as lime or olivine, into a mold.

The blast furnace creates pig iron in a highly exothermic process from sintered iron, additives, coke, and reducing chemicals.

The conversion of pig iron into steel takes place in a basic oxygen furnace. The carbon content of the alloy and its structural characteristics are adjusted by changing the amount of oxygen introduced into the reactor. By adding lime or limestone, the process is kept strongly basic.

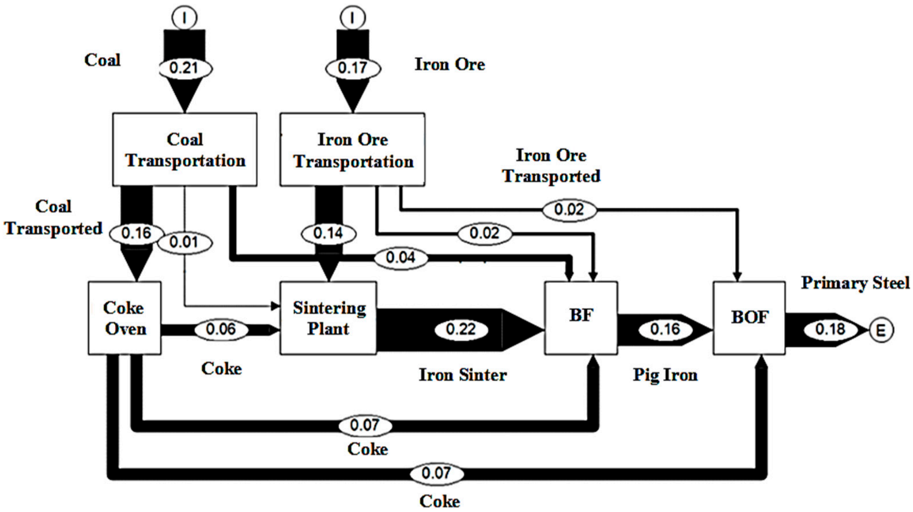


Figure 3. Integrated primary steelmaking process system used for avoided impact calculation.

2.2.2. Decommissioning Operations

Decommissioning operations start at first with platform removal, which implies the use of several marine vessels including a tug boat, a crane vessel or work barge, a barge, and a supply boat.

According to ENI S.p.A. decommissioning project, the phases below will be followed:

1. Pier and landing stage removal;
2. Protection jacket removal;
3. Cleaning of cutting and anchoring points;
4. Lifting bollards positioning;
5. Digging a trench of almost 1.5 m depth from the mudline to allow the cutting operations;
6. Cutting with a diamond wire machine, divers, and ROV;
7. Monotubular lifting and positioning on dumb barge;
8. Transporting the dumb barge to shore using the tug boat;

Monotubular discharging into the yard.

The operations listed last for approximately 15 days.

Calculations of transportation emissions are defined by UE-EMEP guidelines [16], according to which the complex environmental loads are linked to fuel and engine characteristics.

From the assumptions of medium aged vessels, it follows that utilized fleet falls under Tier 2 group; consequently, appropriate emission calculation procedure is based on the following formula:

$$E_i = \sum_m \sum_j FC_{m,j} \cdot EF_{i,m,j} \quad (1)$$

where

E_i = total annual emission;
$Fc_{m,j}$ = type m fuel consumption by a type j engine vessel;
$EF_{i,m,j}$ = type i pollutant average emission factor for type m fuel consumption by a type j engine vessel, calculated by adopting average utilization and travel conditions.

2.2.3. Steel Recycling

According to ENI S.p.A evaluation, material flow composition obtained from the platform is similar to construction and demolition waste flow (Table 1) and is identified as the following [24]:

- Cement and concrete;
- Steel, iron, and type Fe510C-EU25 alloys;
- Coatings and linings;
- Miscellaneous waste, including marine growth estimated at 10% of cement weight.

Table 1. Platform material inventory according to ENI S.p.A. estimates.

Element	Weight [t]
External tube	28
Cement	154.8
Guide tube	15.7
Coating	2.5
Conductor centering	1
Anodes	1
Pier and landing stage	5
Marine growth	15
Total	223

Material waste flow from platform dismantling is composed of 21.8% of steel, 69.4% of cement, and 8.7% of miscellaneous components. Because of that, steel separation and cleaning phase consumptions had been assumed equal to those of construction and demolition waste flow carried out in an electricity-powered fixed treatment plant composed mainly of grinding/shredding, magnetic separation, and sieving phase. Separated material different from steel and iron is collected and sent to the final disposal. The total efficiency of the treatment and separation phase is 99.8% and involves 1 kWh of electricity consumption for each ton of material treated [18].

Steel scrap from the treatment plant is melted in an electric arc furnace by using an electric discharge created by graphite electrodes into the crucible.

2.3. *Life Cycle Impact Assessment*

Environmental assessment is performed using the OpenLCA software by considering "Climate Change", "Human Toxicity, "Cancer Effects", "Land Use", "Marine Eutrophication", "Particulate Matter", and "Water Resource Depletion" about the ILCD2011 characterization factor as proper impact categories. Recalling both foreground and background systems and the fact that system expansion had been applied to calculate all avoided impacts generated by steel platform recycling, the results of the impacts assessment phase are shown in Table 2.

Table 2. LCA results for considered impact categories.

Impact Category	Result
Climate change	3.5×10^3 kg $CO_{2,eq}$
Human toxicity, cancer effects	1.2×10^{-5} CTU_h
Land use	1.6×10^3 kg $C_{deficit}$
Marine eutrophication	9.5×10^{-2} kg $N_{,eq}$
Particulate matter	8.5×10^{-2} kg $PM_{2.5,eq}$
Water resource depletion	1.5×10 $m^3{}_{water,eq}$

2.3.1. Climate Change

The climate change impact category takes into account all greenhouse gas emissions as contributions to the positive warming radiative forcing acting in the climate earth system. By using IPCC's characterization factors over the 100-year time horizon (GWP100), the impact category represents a complete overall index and is expressed through the [kg $CO_{2,\,eq}$] unit measure.

As shown below, even though avoided impacts from steel recycling had been included in the environmental balance, the score for the climate change impact category is positive overall, indicating the project has a negative global impact due mainly to the small amount of steel obtainable from the platform treatment that limits avoided impacts and the high vessel emission factors that make cutting, transportation and discharging in yard phase responsible for significant polluting emissions.

2.3.2. Human Toxicity, Cancer Effects

Human toxicity and cancer effects impact category considers toxicity potential toward humans expressed by the [CTU_h] unit measure that takes into account potential risk associated with each compound based on its inherent toxicity and potential intake. CTUh expresses the increase in morbidity for each unit mass.

Generally, the main sources of toxic compounds are fossil fuel consumption by engines and power plants [25].

As expected, because of the high fuel and energy consumption involved in both platform dismantling at sea and steel recycling activity, the main impacts are attributed to cutting and transportation and the electric arc furnace unit process.

2.3.3. Land Use

Land use evaluation is focused on impacts due to anthropic earth surface consumption expressed by the [kg $C_{deficit}$] unit measure that is the soil organic carbon variation.

In the study, impacts linked to diesel production utilized by vessels during platform dismantling are predominant, net of land use caused by plants involved in the product system.

2.3.4. Marine Eutrophication

Marine eutrophication is a chemical nutrient enrichment inside an ecosystem that causes excessive biomass production usually occurring in basins with low water exchange and entails significant algal blooms and strong water quality reduction.

Water or gaseous ammonia, nitrogen, or phosphorus compounds emissions are typically linked to eutrophication. Characterization factors are based on IPCC's evaluation and expressed through [kg $N_{,eq}$] unit measure.

According to characterization models, eutrophication is caused by transportation, marine operation, and primary steel raw material production. This is mainly due to the combined effects of atmospheric emissions and direct discharge involved in these types of activity [26–28].

2.3.5. Particulate Matter

Particulate material (PM) indicates a complex of particles from carbonaceous ones to salts of both organic and inorganic nature usually classified by average dimension. The main PM sources are vehicle and domestic combustion processes and abrasive operations involved in different and heterogeneous processes. Particulate matter impact category utilizes [kg $PM_{2.5,eq}$] as category index.

Once defined PM sources, comes easily that primary steel coal production and diesel used in marine transportationare the major particulate sources.

Note that electric arc furnace electricity consumption does not generate significant PM emissions since Italian energy sources are strongly based on renewables (approximately 45%) and natural gas (approximately 42%) [29].

2.3.6. Water Resource Depletion

Water resource depletion is expressed by [$m^3{}_{water,eq}$] unit measure and its impact is primarily due to marine vessel diesel production.

2.4. Contribution Analysis

Figure 4 represents the contribution analyses for all impact categories considered. The contribution analyses refer to the functional unit of 1 tonne of decommissioned monotubular offshore platform.

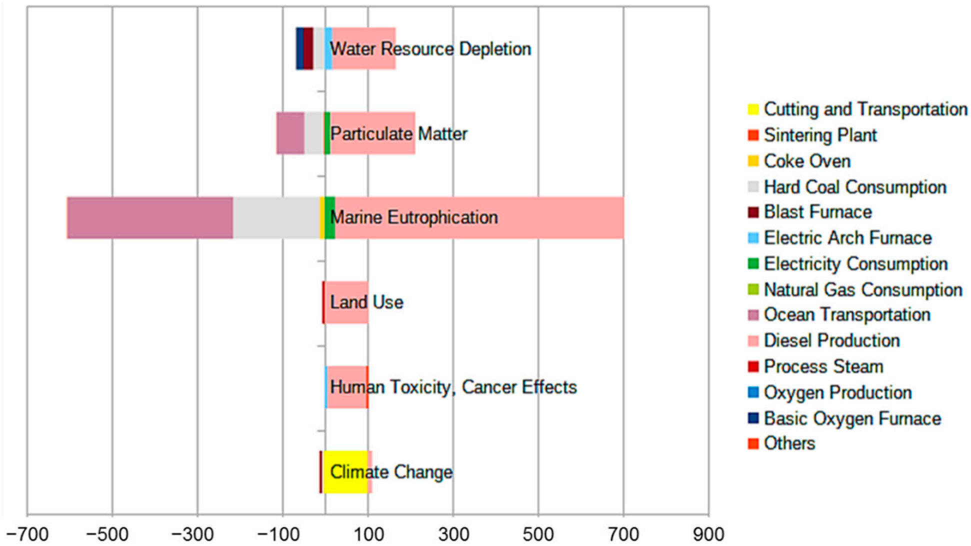


Figure 4. Barplot of unit process contributes to total impact categories values.

Table 3 shows the results of the analysis in percentage terms for all process units.

Table 3. Contribution analysis per unit process.

	Climate Change	Human Toxicity, Cancer Effects	Land Use	Marine Eutrophication	Particulate Matter	Water Resource Depletion
Cutting and transportation	101.8%					
Sintering plant	−2.57%				−2.28%	
Coke oven	−3.43%			−11.48%		
Hard coal consumption	−5.02%	−0.59%	−2.59%	−202.53%	−44.92%	−26.29%
Blast furnace						−23.16%
Electric arc furnace		6.95%				18.81%
Electricity consumption		0.45%		25.05%	14.19%	
Natural gas consumption						
Ocean transportation		−0.16%		−388.35%	−65.02%	
Diesel production	9.88%	93.3%	102.58%	678.57%	198.6%	148.41%
Process steam						
Oxygen production						
Basic oxygen furnace						−17.16%
Others	−0.65%	0.05%		−1.26%	−0.56%	−0.6%

In the end, it is necessary to highlight that LCA analyses to date have only considered abiotic assessments based on chemical and physical parameters due to the difficulty of identifying appropriate biotic indicators, impact categories and characterisation models. In fact, all the decommissioning operations may involve or cause impacts over both habitat, biota and mudline. In particular, there are high menaces to biodiversity caused by the loss of fragile marine habitat connected to the structure [30–34], disturbance to vulnerable species [35–37], and the destruction of the barrier effect provided by the platform [36,38–40]. Total removal of the platform also causes the loss of the food chain made in decades around the structure [34,38,41,42], the alteration of the seabed that can affect especially sessile benthic species [30,31,38,40,43,44] and the permanent modification of hydrographic conditions [30,40,41,45–51]. Moreover, offshore operations may introduce macro and micro pollutants (i.e., chemicals, organic and inorganic compounds, heavy metals, etc.) [37,52] as well as energy and vibrations [30,31,37,53,54].

However, there is much room for improvement in filling the gap of the lack of biotic impact categories to assess the environmental damage to ecosystems, not in terms of resource depletion or changes in chemical compounds, but in terms of the loss of ecosystem services due to habitat destruction and the consequent loss of flora and fauna resulting from the total removal of offshore platforms.

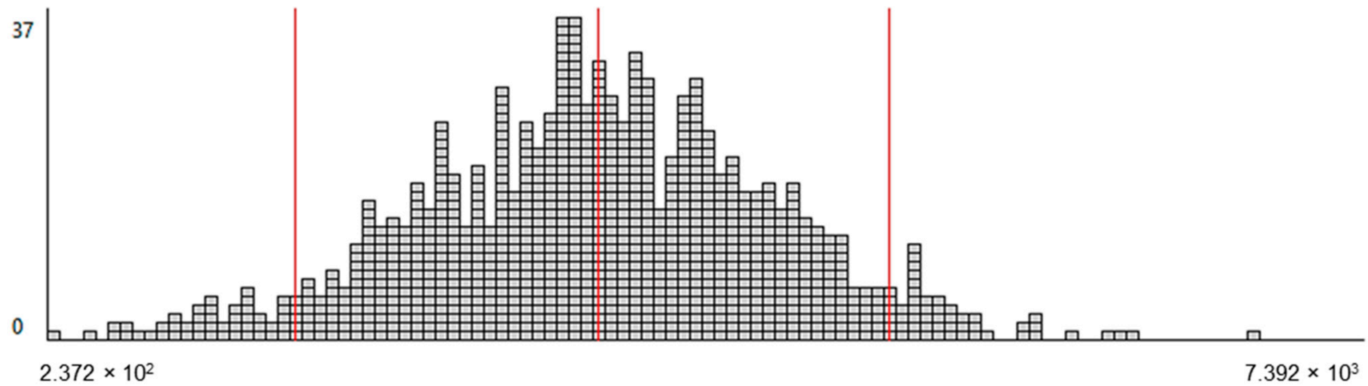
2.5. Life Cycle Interpretation

In this section, LCA results and their main characteristics will be discussed as well as uncertainty analysis, data quality and sensitivity analysis. Finally, an economic impact assessment of decommissioning project will be presented to provide the chance to evaluate possible alternatives to total removal as planned by the owner.

2.5.1. Uncertainty Analysis

Due to the aleatory nature of the dataset, based on the average literature data, it is worthwhile to evaluate the uncertainty affecting the results and their distribution through a Monte Carlo simulation (MC). MC performed a random set of simulations varying the input data for the calculations based on the distributions of the different parameters.

Uncertainty analysis was conducted by evaluating uncertainties for each inventory item where a variance estimate was available. Therefore, given that the LCA inventory phase required literature references in the form of an average dataset, through OpenLCA uncertainty analysis, a statistical distribution was attributed for each parameter and the normal distribution was selected for the entire inventory. Figure 5 shows the 1000 MC simulations and Table 4 shows the main statistics for each LCA impact category obtained by these simulations.



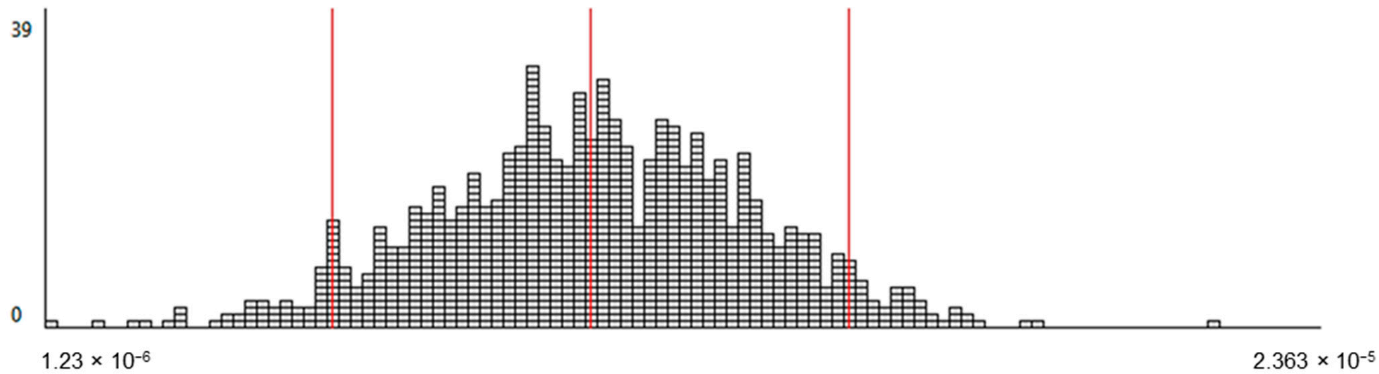


Figure 5. *Cont.*

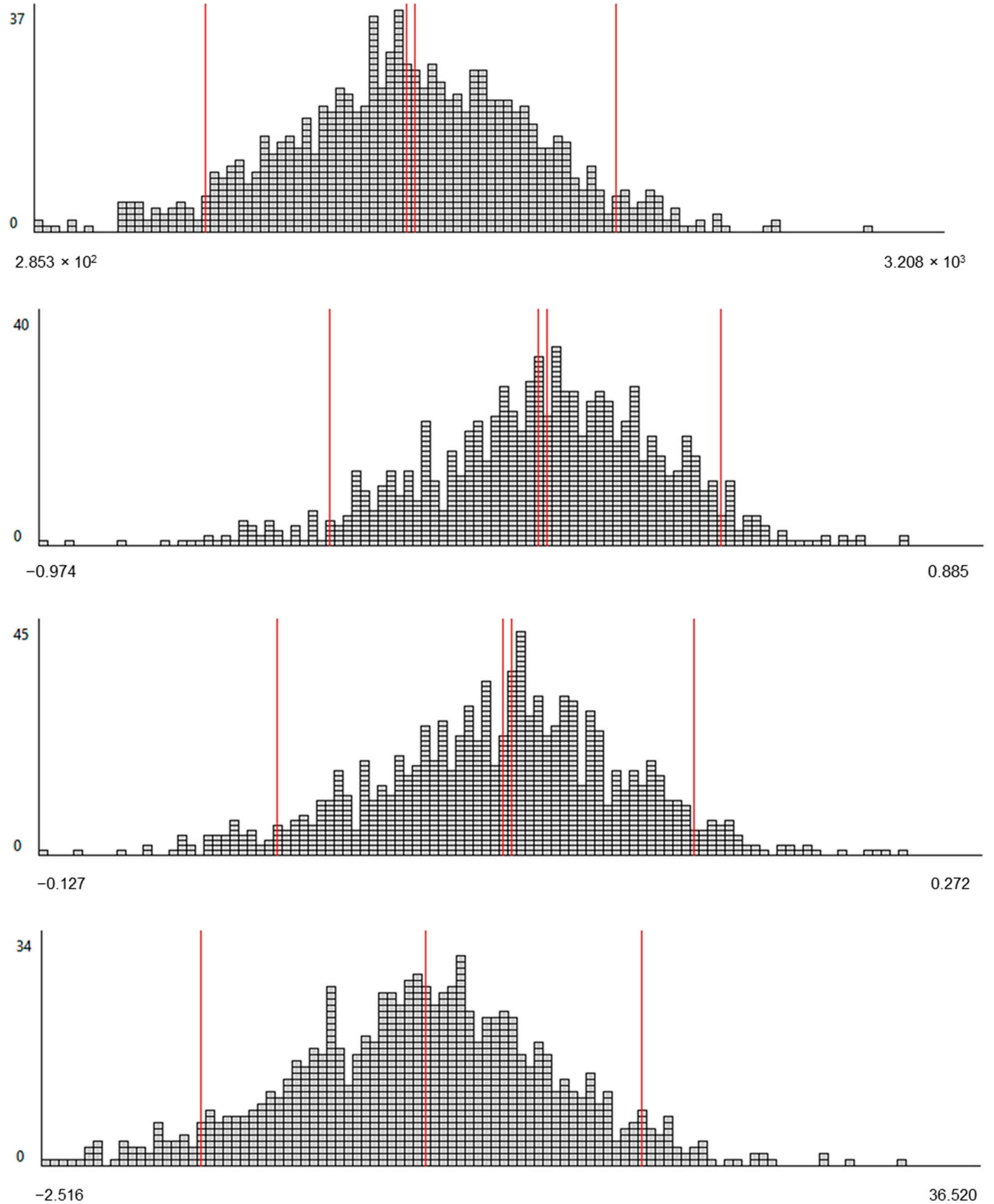


Figure 5. Statistical distribution of results for each impact category (in order: climate change, human toxicity, land use, marine eutrophication, particulate matter and water resource depletion). Red lines depict mean, median and standard deviation as visual representation of data dispersion.

Table 4. Normal statistical distribution properties of results.

	Mean	St. Deviation	Median	5% Percentile	9% Percentile
Climate change	3.5×10^3	1.04×10^3	3.5×10^3	1.74×10^3	5.24×10^3
Human toxicity, cancer effects	1.17×10^{-5}	2.99×10^{-6}	1.17×10^{-5}	6.72×10^{-6}	1.65×10^{-5}
Land use	1.6×10^3	4.33×10^2	1.59×10^3	8.85×10^2	2.32×10^3
Marine eutrophication	0.102	0.261	0.119	−0.344	0.494
Particulate matter	0.085	0.058	0.09	−0.016	0.175
Water resource depletion	14.75	5.94	14.9	4.62	24.49

2.5.2. Data Quality Check

The quality of data had been assessed by completing the 5 × 5 matrix of the Ecoinvent data quality system [10]. As shown in Table 5, this evaluation system considers a score from 1 to 5 given to 5 indicators (reliability, completeness, temporal correlation, geographical correlation, and further technological correlation). For each indicator, different quality class values are assigned which compete to assess the final quality score.

Table 5. Description of each quality class and indicator according to Ecoinvent quality data system.

Class\Indicator	1	2	3	4	5
Reliability	Verified data based on measurements	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g., by an industrial expert)	Non-qualified estimates
Completeness	Representative data from all sites relevant to the market is considered over an adequate period to even out normal fluctuations	Representative data from > 50% of the sites relevant for the market is considered over an adequate period to even out normal fluctuations	Representative data from only some sites (<<50%) relevant for the market is considered or >50% of sites but from shorter periods	Representative data from only one site relevant for the market is considered or some sites but from shorter periods	Representativeness unknown or data from a small number of sites and shorter periods
Temporal Correlation	Less than 3 years of difference in the period of the data set	Less than 6 years of difference in the period of the data set	Less than 10 years of difference in the period of the data set	Less than 15 years of difference in the period of the data set	Age of data unknown or more than 15 years of difference to the period of the data set
Geographical Correlation	Data from an area under study	Average data from a larger area in which the area under study is included	Data from an area with similar production conditions	Data from an area with slightly similar production conditions	Data from an unknown or distinctly different area (North America instead of the Middle East, OECD-Europe instead of Russia)
Further Technological Correlation	Data from enterprises, processes, and materials under study	Data from processes and materials under study (i.e., identical technology) but different enterprises	Data from processes and materials under study but different technology	Data on related processes or materials	Data on related processes on a laboratory scale or from different technology

Table 6 shows data quality check of results referring to class and indicators described above.

Table 6. Data quality of results.

Impact Category\Indicator	Reliability	Completeness	Temporal Correlation	Geographical Correlation	Further Technological Correlation
Climate change	2	3	3	4	3
Human toxicity, cancer effects	2	2	2	3	2
Land use	-	-	-	-	-
Marine eutrophication	2	2	2	3	2
Particulate matter	2	2	2	3	2
Water resource depletion	2	2	2	3	2

2.5.3. Sensitivity Analysis

Sensitivity analysis and data quality check are used to evaluate LCA results reliability and their stability with respect to parameter variability.

Sensitivity analysis was performed by varying the 5 main parameters: tons of platform removed (a); platform steel content in percentage by mass (b); average vessel days of effective operation (c); primary steel iron ore supply distance (d); primary steel coal supply distance (e) and evaluating their effect on the impact categories. As an example, the sensitivity analysis result for Climate Change impact category is shown below.

As shown in Figure 6, tons of the platform considered negatively affect all impact categories. This is because the heavier the weight of the platform removed, the higher the recovered steel quantity is obtained and consequentlyrelated avoided impacts are higher.

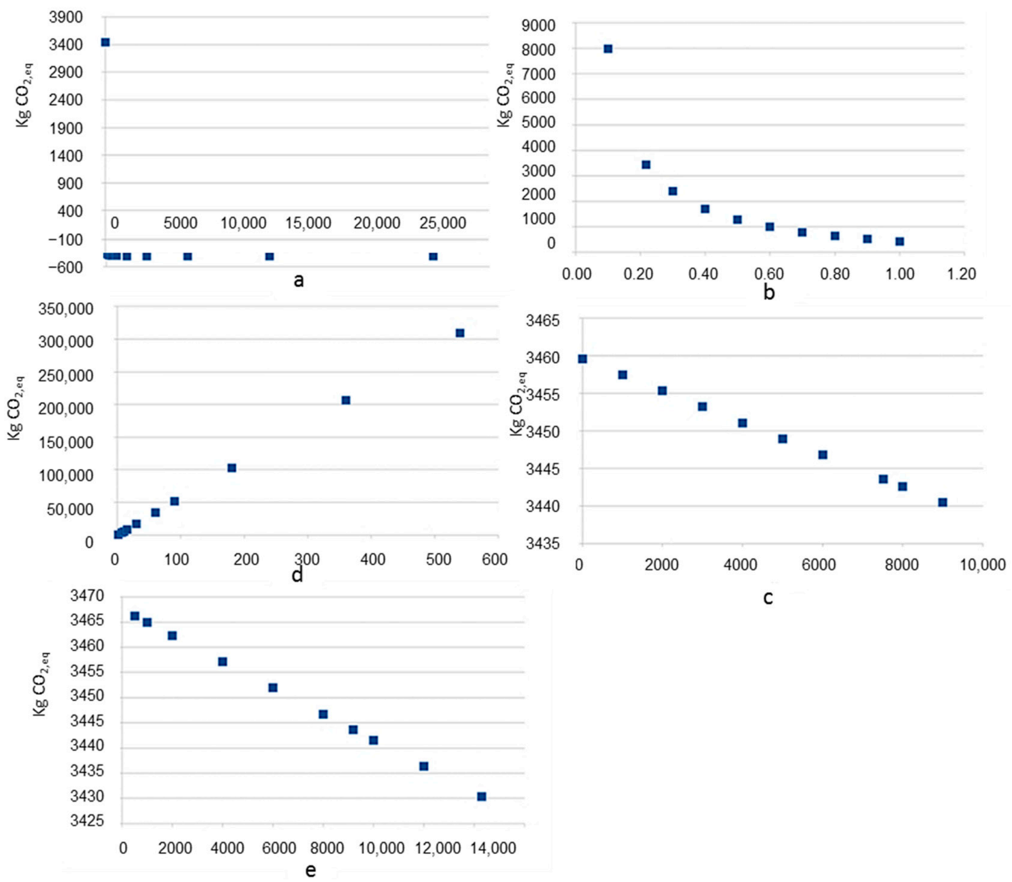


Figure 6. Representation of sensitivity analysis results for each parameter of the Climate Change impact category tons of platform removed (**a**); platform steel content in percentage by mass (**b**); average vessel days of effective operation (**c**); primary steel iron ore supply distance (**d**); primary steel coal supply distance (**e**).

The same applies to platform steel content directly linked to avoided impacts of primary steel replaced by secondary steel produced from platform steel recovered.

However, concerning decommissioning operations, cutting and transportation impacts are linked almost linearly to marine operation complexity that reflects on the greater project schedule.

Primary steel coal and iron ore supply distance influence the LCA results both negatively and in a similar way, resulting in higher avoided impacts with the increase in supply range.

In brief, all parameters analyzed can qualitatively influence LCA results so they should be carefully assessed.

3. Economic Impact Assessment

Economic impact assessment of decommissioning project under study shows the main costs involved in the platform removal and treatment (Table 7), describing each step and recalling the operations involved. The evaluation can be used to assess economic feasibility of reconversion or reuse project as proper alternative to the planned total removal.

Table 7. Costs inventory according to ENI S.p.A. decommissioning project estimates.

Item	Cost [€]
Engineering and project management	180,000
Marine vessels	700,000
Offshore operations	1,200,000
Removal, treatment and recycling	70,000
Insurance and other costs	80,000
Total	2,230,000

3.1. Preparatory Phase

Before the cutting phase, it is necessary to remove marine growth from each mooring and then dig a trench 7.5 × 5.5 large and almost 1.5 m in depth from the mudline.

Once placed, the scaffolding and marine vessels start the securing of the pier, landing stage, and each anchoring point.

3.2. Removal Phase

Once fixed, the loading bitts are loaded to sustain 70% of the total platform weight and then start the cutting operation using divers and ROV.

At the end of the cutting phase, the whole platform is lifted and placed on the dumb barge which is towed to shore and discharged in the yard.

During all the operations, the following marine vessels are utilized:

- 1 dumb barge;
- 1 crane vessel/work barge with ROV;
- 1 supply vessel;
- 1 tug boat.

3.3. Monitoring Phase

The environmental monitoring program is a mandatory phase in O&G decommissioning programs that aims to identify potential negative effects on the environment linked to decommissioning operations through geomorphologic, chemical, physical, and biological analysis carried out in two parts, before and after decommissioning operations, focusing on water, sediments, and benthic population characterization. According to platform dimensions, weight and environmental sensitivity of the area, this step may lead to significant costs.

4. Conclusions and Future Work

The Life Cycle Assessment conducted in this study has enabled the identification of the main environmental impacts associated with the "Viviana 1" platform decommissioning project within the framework of the assumptions described in the objectives and scope phase.

The foreground LCA system includes the preliminary, cutting, and transport operations, the separation and treatment of the steel removed from the platform, recycling operations, and the related avoided impacts calculated by expanding the system boundaries and considering the production of primary steel in an integrated steel plant.

In summary, results show that the activity of marine vessels and the related production of diesel fuel represent the main environmental impact factors for all impact categories considered.

Finally, the influence on results of platform weight, platform steel content, days of marine operations, and distance of coal and iron ore supply was evaluated through a sensitivity analysis that highlighted the following key points:

a. Tons of platform decommissioned, represented by parameter a, are decreasingly hyperbolic linked to all impact categories.
b. Steel content of platform, represented by parameter b, is decreasingly hyperbolic linked to all impact categories.
c. Average number of vessel days of effective operation, represented by parameter c, is positively linearly linked to all impact categories.
d. Primary steel iron ore supply distance and primary steel coal supply distance, represented, respectively, by parameters d and e, are inversely and linearly linked to all impact categories, but Land Use that does not change the parameters e and d varies.

Despite the fact that the current analysis contains strong assumptions about site, treatment, recycling phases and location which make it less specific and offer ample room for improvement, it clearly represents the entire product system involved in platform decommissioning and enables to make some important considerations about total removal and consequent steel recycling system:

a. As expected, final results of the LCA are mainly influenced by platform type and structure as well as its distance from the shore yard.
b. Most of environmental impacts are linked to marine vessel operations for platform removal and the relative fuel production and consumption.
c. The entire processes of steel recycling may play an important role in the final environmental performance assessment as avoided impacts, recalling that the more impacting (economically and environmentally) the primary steel production, the more sustainable the choice of recycling platform steel through electric route.
d. As a consequence of the previous point, material flow steel content obtainable from platform dismantling strongly affects the total avoided impacts and it represents a decisive parameter to assess the environmental sustainability of this kind of project.
e. Concerning the economic analysis, the major costs are expected to be connected to offshore operations and marine vessel and working crew rentals.

Given the nature of the project and its influence on the environment as a sum of ecosystem services, biotic impacts must also be considered and quantified by formulating appropriate impact categories. Indeed, an ecosystem-based view can help to thoroughly assess the future perspective of offshore platforms by properly analysing different decommissioning practices.

In view of this and of the significant costs associated with the decommissioning process, as well as the environmental considerations of the negative externalities produced, there is a gradual shift in international guidelines paving the way for a more flexible approach based on partial removal or conversion of installations. The hypotheses of alternative uses that can combine different activities with respect to the reference context also require new approaches that aim to extend the structural life of offshore platforms without neglecting the environmental aspect [55,56]. Furthermore, in future phases, an economic assessment through the Life-Cycle Cost–Benefit methodology could help oil and gas industry managers to quantify decommissioning costs or estimate maintenance costs compared to future revenues, or even to assess the advantages and disadvantages of starting a particular activity.

Ultimately, the study provides a sound preliminary analysis and basis for future studies on offshore platform decommissioning and its impacts, integrating multi-level environmental assessments through an interdisciplinary approach useful for authorities and stakeholders involved in decision making. The importance of a clear and systemic governance framework appears crucial to support the actors involved and the feasibility of these operations, providing food for thought for researchers and practitioners.

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