

Article

Life Cycle Assessment of Electro-Submersible Pump Systems: Carbon Footprint Mitigation Using Improved Downhole Technology

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Abstract: Climate change has driven global awareness of environmental issues, leading to the adoption of clean technologies aimed at reducing Greenhouse Gas (GHG) emissions. An effective method to assess environmental mitigation is the quantification of the Product Carbon Footprint (PCF) in the Life Cycle Assessment (LCA) of production processes. In the oil extraction industry, artificial lift systems use electro submersible pumps (ESPs) that can now incorporate new operating principles based on permanent magnet motors (PMMs) and CanSystem (CS) as an alternative to traditional normal induction motors (NIMs) and can help lower the carbon footprint. This study compares the PCF of ESPs equipped with PMMs and CS versus NIMs, using LCA methodologies in accordance with ISO 14067:2018 for defining the Functional Unit (FU) and ISO 14064-1:2019 to calculate the GHG inventory and the amount of CO₂ equivalent per year. The analysis spans five key stages and 14 related activities. For ESPs with NIMs, this study calculated 999.9 kg of raw materials, 1491.66 kW/h for manufacturing and storage, and 5.77×10^4 kW/h for use. In contrast, ESPs with PMMs and CS required 656 kg of raw materials and consumed 4.44×10^4 kW/h during use, resulting in an 23% reduction in energy consumption. This contributed to an 21.9% decrease in the PCF. The findings suggest that PMMs and CS offer a sustainable solution for reducing GHG emissions in oil extraction processes globally.

Keywords: climate change; greenhouse gas emissions; life cycle assessment; electro-submersible pumps (ESPs); permanent magnet motors; normal induction motors; carbon footprint



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1. Introduction

Climate change affects all regions of the world. Polar ice caps melt, and sea levels rise. In some regions, extreme weather events and floods are becoming more frequent, while in others, heatwaves and droughts are being recorded [1]. Emissions of GHG such as (a) carbon dioxide (CO₂), (b) nitrous oxide (N₂O) and the fluorinated gases (HFC, PFC and SF₆), are released into the atmosphere and trap the sun's heat, leading to global warming and climate change [2,3]. These gases come mainly from human activities such as (a) electricity generation, (b) manufacturing, (c) deforestation, (d) transportation, and (e) food

production, among others. Most greenhouse gas emissions are generated in industrial processes, of which 9.7% corresponds to oil activities. Artificial oil lifting accounts for 93% of cases, using Electro-Submersible Pump Systems (ESPs) in wells [4]. However, there are few studies on the quantification of GHG emissions and their inventories throughout the life cycle assessment (LCA). In 2022, 197 countries agreed to: (a) quantify and (b) report GHG emission inventories, generated by the execution of anthropogenic activities and sinks using similar and traceable methodologies [5,6].

In the oil extraction industry, the technology used to configure the ESPs is a function of the final production rates and the type of oil in the reservoir. Although the technology of motors and spare parts comes from prior engineering carried out in a simulator called AutographPC®, this computer tool only has the normal induction motors (NIMs), which are the ones provided by Baker Hughes for its worldwide clients, which limits the analysis with other engines that are not constant in the program memory. In spite of this, due to the high costs of electrical energy consumption and competition in the sector to gain new clients, service providers have seen the need to generate innovative projects with new ESPs adjustments that offer customers new alternative models not only to reduce electricity consumption but also to meet the goals of their management systems and benefit from reduction in taxes by the Ecuadorian government for using cleaner technologies. Therefore, quantifying the LCA for an ESPs with new engine operating technologies as part of its components to achieve environmental benefits becomes a necessary task. It is possible to mention that companies dedicated to artificial oil lifting protect their innovations with patents and intellectual property registrations in the competent bodies of each country where they carry out their operations to avoid copying their ESPs configurations. Therefore, they do not usually disclose their results explicitly unless it is to assert the authorship of some new technology or in oil congresses that they consider relevant, with the aim of securing possible service agreements with new clients.

To develop a comprehensive GHG emissions quantification system at the organizational level requires quantifying the carbon footprint of all emissions; the reference guide is ISO 14064-1:2019 [7]. On the other hand, different methodologies help provide more details on the three scopes defined by this standard (direct, indirect and other sources of contamination), including (a) the World Business Council for Sustainable Development (WBCSD) and World Resources Institute (WRI) GHG Protocol, which categorizes energy emissions into 15 subcategories, and (b) the Intergovernmental Panel on Climate Change (IPCC) guidelines [8], allowing flexibility in inventory calculations using methods of varying complexity. The methodology for calculating the CF begins with quantifying the GHG emission inventory, which is based on consolidating available data into a summative data register and applying emission factors for each emission source. However, the concept of organization does not fully contribute to the understanding of GHG emission control, as it only considers polluting activities within the administrative environment of the company.

Currently, GHG emission inventory calculations consider not only a single activity or project but the entire LCA of the product or service. A viable alternative for this is to use the ISO 14067:2019 standard [9]. This standard helps calculate the GHG emission inventory by defining a Functional Unit (FU) according to ISO 14040:2006/A2:2021 [10], influencing an environmental impact result, such as the CF, for the entire manufacturing process of the product or service. Therefore, proposing environmental management and control in process activities without creating a GHG emission inventory is not feasible.

On the other hand, local government-promoted air quality measurements follow specific methodologies to quantify pollutant emissions at exposure points, not considering the specificities outlined in the ISO 14067:2019 family of standards for quantifying kg of CO₂ equivalent for year (CO₂ eq/year), such as: (a) the LCA of the product determined by

ISO 14044:2006/A2:2021 [11] and (b) energy and mass balances at each stage of product or service manufacturing. However, not all GHG emission inventory cases need to quantify CO₂ eq/year until the final processes, as sometimes the output is an input for another production system. To address this premise, two production cycle options are considered: (a) from cradle to grave and (b) from cradle to gate [12,13].

When processes involve many activities and input resources, computational tools are used to handle complete GHG emission inventory databases and facilitate quantification. Among the most used inventory and LCA calculation tools are: (a) CCalC2, (b) OpenLCA, and (c) GEMINIS, which considers inventories as inputs to simulate and study atmospheric processes and global changes in production activities and organizations [14]. Although business initiatives to reduce CF and GHG emission inventory are numerous, it is crucial to consider the most feasible alternatives. In the manufacturing of an ESPs, innovations and solutions to reduce GHG emissions are costly. However, efforts can be concentrated on saving electrical energy, as this resource is used continuously for operation.

While induction motors provide a reasonable Productivity Index (PI), permanent magnet motors can be used to reduce electricity consumption, increase flow, and PI. This research calculated and compared the CF using CCalC2 [15], under normal manufacturing conditions of an ESPs assembled with a Permanent Magnet Motor series 440 of 11.16 m and 120 Hz, and one with a Normal Induction Motor 450 in a field operated by Baker Hughes and CS located in conglomerate areas. CS For this design, a compressor pump and an intake were selected due to the characteristics of the sand to be produced and the encapsulated system. In addition, the selected seals can retain contamination from the well fluid while managing the downward thrust generated by the pump stages. The sensor used is a robust and reliable Zenith E7 sensor. For the power cable, cable #2 SOL was used. 5KV $\times$ 2Cap 3/8' S.S. The controller works with more than 200KVA. Simple horizontal splices were used as a viable environmental solution.as a viable environmental solution.

2. Materials and Methods

2.1. Life Cycle Analysis (LCA) of the Product

To quantify CF, it is necessary to map the LCA processes of the product or service [16]. This map provides a comprehensive breakdown of: (a) services, (b) input and output materials at each unit process, and (c) the energy required to move a product or by product through the activities of its LCA. This results in a more efficient GHG emissions inventory.

To determine the LCA in the assembly of an ESPs, actual data on materials, equipment and energy consumption must be considered (materials originating in the United States). In this research, the average data from 12 oil wells under similar production conditions and reservoir fluid properties with their temperature and pressure variations, known as Pressure-Volume-Temperature (PVT), were used.

The GHG emissions generated by transport vehicles are those recommended by CCalC₂ for a 22-ton truck.

In addition, recycling of the ESPs at LCA was not considered in this research because the reuse or repowering of the engines occurs simultaneously when Baker Hughes' in-shop materials inventory requires it, and the department's information considers costs like the acquisition of a new engine with a recycled one.

Before establishing the inventory quantities, an analysis must be performed at each stage of the LCA of the manufacturing of an ESPs with the help of all Baker Hughes stakeholders from cradle to grave in the process map for the LCA that applies to the manufacturing of an ESPs at Baker Hughes according to the ISO 14067:2019 [9] and GHG protocol. See Figure 1.

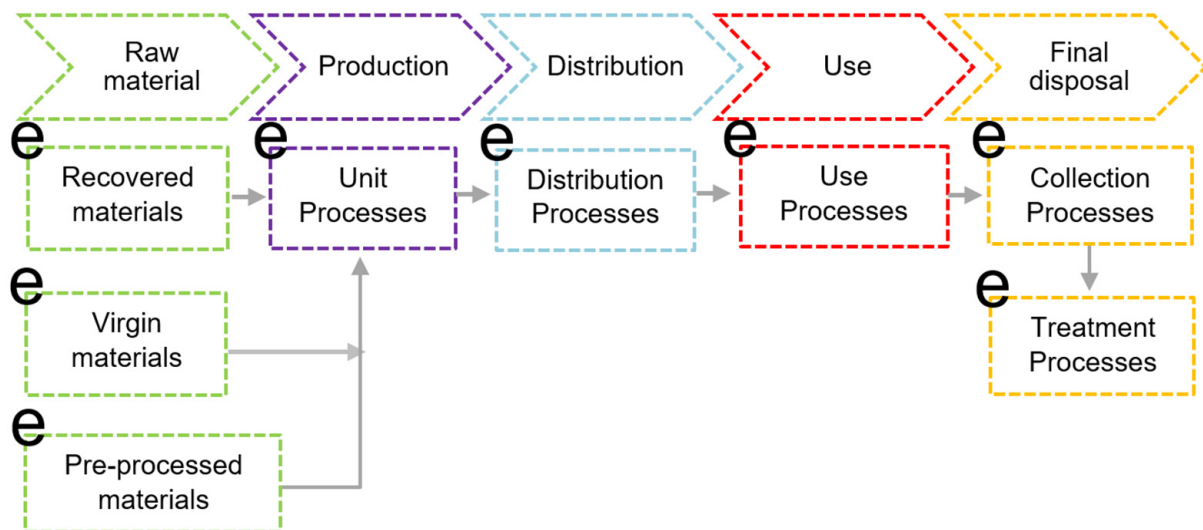


Figure 1. Life cycle assessment of a product. The gray arrows indicate material transport. e = energy. Adapted from GHG product life cycle accounting and reporting standard.

2.2. Greenhouse Gas (GHG) Emissions Inventory and LCA

The inventory first requires defining the inputs and outputs of each of the processes outlined in the LCA of the product or service. For the researcher's convenience, ISO 14027 [17] provides guidelines for activities and unit processes for the manufacturing of some products. While these Product Category Rules (PCRs) help standardize manufacturing activities, they do not cover all manufacturing cases and are even less so for services. Next, the GHG emissions must be quantified for: (a) materials and (b) energy sources at each stage of the LCA defined for the product or service.

To perform the quantification, it is necessary to establish the quantity of the reference product or service for the entire inventory calculation, establishing a Functional Unit (FU) according to ISO 14067 [18]. This research considers an ESPs assembled by Baker Hughes as the FU. Finally, the carbon dioxide equivalent (CO_2 eq.) weight of the entire inventory is summed and calculated, accordance with ISO 14067:2019 [9].

To deepen the analysis of the inventories, GHG emissions are classified according to ISO 14064 [7], grouping the quantities into three sources: (a) direct, (b) indirect, and (c) energy. To determine the GHG emissions inventory in the LCA of manufacturing an ESPs. The following inputs were defined: (a) Electric Submersible Pump, (b) electrical energy, (c) transportation energy, (d) packaging and (e) waste. This applies to each stage of the LCA. Figure 2 describes the complete process for calculating product carbon footprint (PCF).

2.3. Quantification of the Product Carbon Footprint (PCF) of the Electrical Submersible Pump (ESP) System

After determining the Functional Unit (FU), defining the scope and, LCA, and developing the GHG Emissions Inventory, the emissions must be quantified following Equation (1), considering the scopes defined in ISO 14064 [7].

$$E = AD \times ED \times GWP, \quad (1)$$

were:

E = Emissions concentration in weight of CO_2 equivalent

AD = Activity Data

ED = Emissions Data

GWP = Global Warming Potential

The main objective of this study is to compare the CF of assembling an ESP with a NIMs and the CF of assembling an ESP with a PMMs.

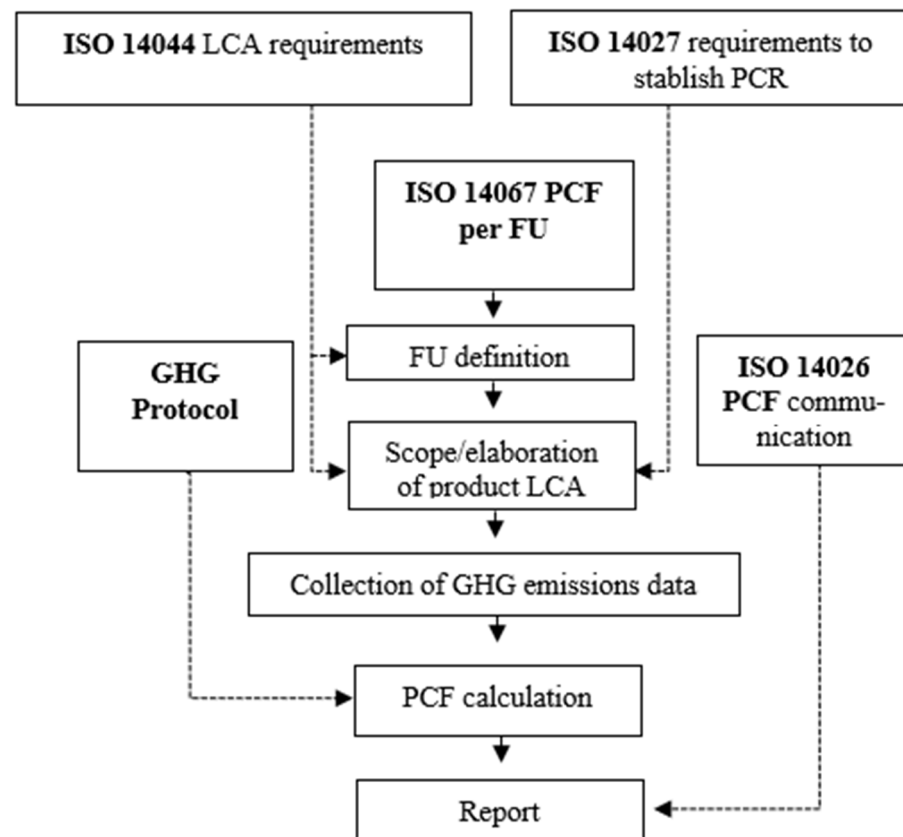


Figure 2. Complete process for calculating product carbon footprint (PCF). LCA = life cycle assessment. PCR = Product Category Rules. FU = Functional Unit.

Once the activities of each stage of the LCA for the manufacture of the ESPs have been determined, the E must be calculated. To accomplish this, it is necessary to carry out a complete inventory for each activity, whether input or output. However, after having the inventory at each stage of the LCA, it is necessary to know the: AD, EG and GWP so the use of computer tools with complete databases is of great help. A viable alternative is CCaLC₂. CCaLC₂ is the second generation of the CCaLC tool, which was developed by the Sustainable Industrial Systems at the University of Manchester under the ISO standard. In its most robust and desktop version, CCaLC₂ allows the assessment of seven types of environmental impacts: (a) PCF, (b) product water footprint, (c) acidification potential, (d) eutrophication potential, (e) ozone depletion potential, (f) photochemical smog potential, and (g) human toxicity potential. Its calculation methodology is based on the ISO 14067 and PAS 2050 standards [19]. This software has three extensive databases to go from: (a) quantity of process and sub-process materials, (b) type of energy and (c) type of transport at each stage of the inventory to the equivalent amount of CO₂ per year.

3. Results

3.1. Result of the Life Cycle Assessment (LCA) of the Manufacturing of an ESPs

To obtain the priority activities, the macro activities detailed in the ESP manufacturing procedures developed by Baker Hughes were selected. The materials, equipment and energy consumption required to prepare the LCA of the manufacturing of an ESP were taken from actual data for one year of use under normal operating conditions. In addition, a study of times and movements of the materials and vehicles required in each of the

manufacturing stages according to the Baker Hughes ESP assembly procedures was carried out to determine the total energy use.

To assemble an ESP at Baker Hughes, 14 activities were identified in the manufacturing process from cradle to grave. Although the input materials involve individual manufacturing processes with the generation of GHG emissions, the CCalC2 database was used. The inventory process map of the LCA of an ESPs does not include final disposal or delivery to competent bodies for waste treatment since, at Baker Hughes, most components are reused and upgraded due to environmental policies and goals. The LCA of the ESPs manufactured with both the IM and the PMM, produced and operated by Baker Hughes, includes the averages of actual consumption from 12 wells, validated by the engineering department. Figure 3 provides a more graphic representation of LCA considering all activities.

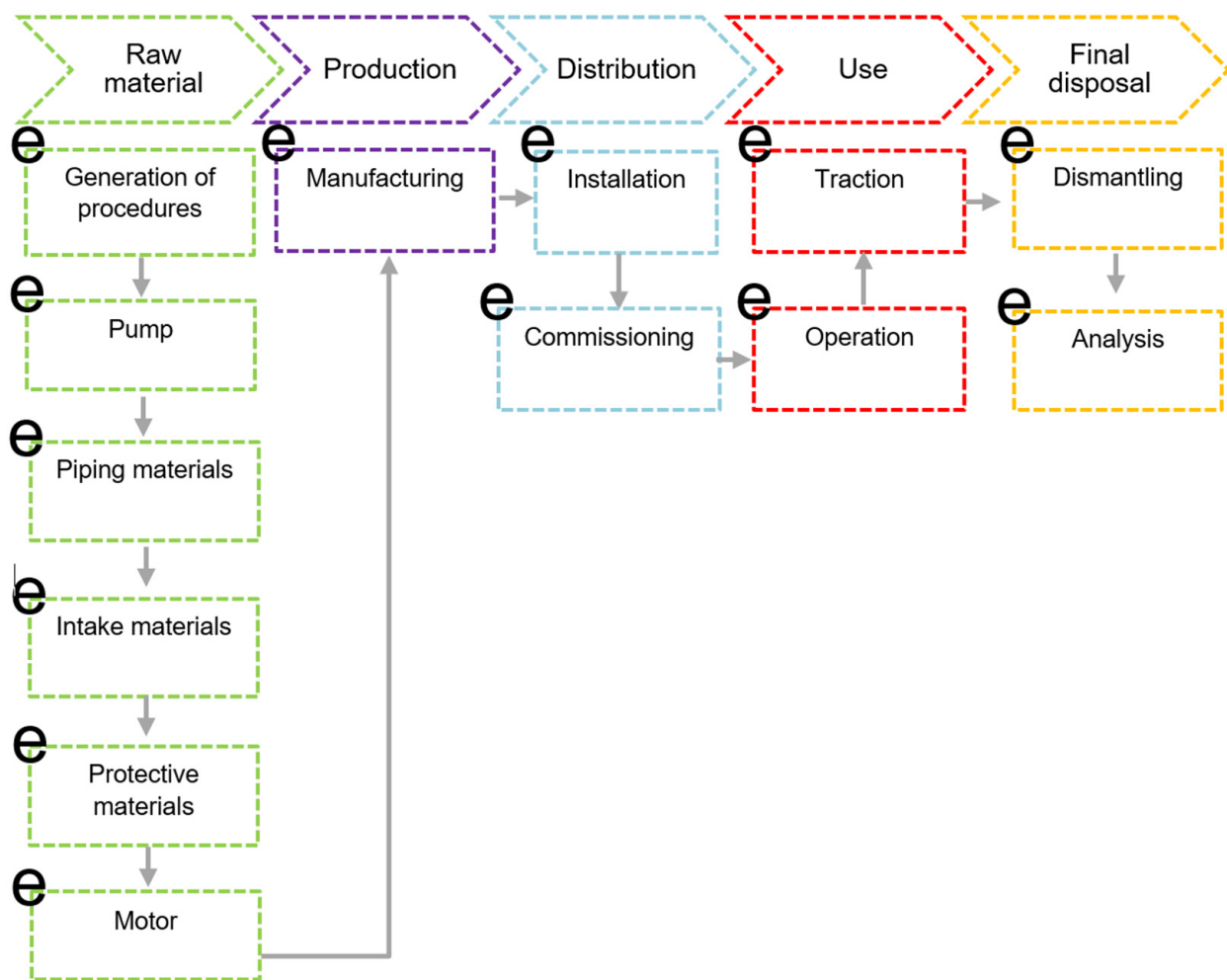


Figure 3. Life cycle assessment for the assembly of ESPs. Gray arrows indicate material transport. “e” represents energy.

3.2. Result of the GHG Emissions Inventory in the Assembly of an ESPs

The quantities of greenhouse gas emissions were calculated in the assembly of an Electric Submersible Pump with a Normal Induction Motor of 60 Hz, series 450. Table 1 shows the accumulated results at each stage of manufacturing, considering historical data from Baker Hughes’ Engineering department.

Table 1. Greenhouse gas inventory for Electric Submersible Pump with Normal Induction Motor.

Parameters	Unit	Raw Material	Manufacturing	Storage	Use
Electric Submersible Pump	kg	997.90	0	0	0
Electrical energy	kW/h	0	0	0	5.77×10^4
Transportation energy	kW/h	0	1491.66	1491.66	0
Packaging	kg	0	0	0	0

The ESPs consist of: (a) pipe materials, (b) inlet materials, (c) protector materials, and (d) motor. The Functional Unit is one ESPs manufactured by Baker Hughes. The calculated data is the average of the PVT conditions of the 12 reference wells using the PMMs. These include an oil gravity range of 788 to 920 kg/m³, a gas gravity between 0.65 and 1.276, and a separator pressure and temperature of 2.86 MPa and 52 °C. The location and installation facilities of the ESPs in the oil fields were those provided by: (a) four wells in Petro Ecuador, (b) five wells in Block 16, (c) one well in Pardalis Services and (d) two in Andes Petroleum.

The main data on the inventory of materials, equipment, transportation times of materials from suppliers to the pre-assembly shop and subsequent location at the ESP installation site were provided by the engineering department of Baker Hughes in the period 2021–2024. In addition, data on material weight and energy consumption in the assembly of the 664 wells operated by Baker Hughes with PMMs were used. Their locations were as follows: (a) 320 in Argentina, (b) 189 in Colombia, (c) 134 in the United States, (d) 14 in Canada, (e) 12 in Ecuador, (f) 5 in China, and (g) 3 in Oman.

For this research, the actual energy consumption data from the 12 oil wells were distributed as follows: (a) four wells in Petro Ecuador, (b) five wells in Block 16, (c) one well in Pardalis Services and (d) two in Andes Petroleum. Also considered were: (a) variations in oil content and water cut with a range of 788 to 920 kg/m³ for oil gravity and 0.65 to 1.276 for gas gravity, (b) formation pressure in a range of 1000 to 3000 PSI; (c) depths and deviations of the wells in a range of different depths and specific deviations according to the engineering design of each well and (d) Production requirements, which depend on the needs of each client according to their location, reservoir characteristics, and operating conditions.

Some of the ESP configuration data are results of nodal analysis resulting from the engineering design in PROSPER and the design of the elements with AutographPC® developed by Baker Hughes personnel. The weight and energy determined at each stage is the sum of each life cycle element defined for the manufacture, use, storage and reuse of an ESPs operated by Baker Hughes defined in Figure 2. Table 1 shows the total sum of materials in kg and energy in kW/m² for each activity determined in the inventory for the LCA of the manufacture of ESPs from cradle to grave with the use of an NIMs.

The energy expenditure includes the movement of materials to Baker Hughes locations and then to end-use sites. The ESPs consist of: (a) pipe materials, (b) inlet materials, (c) protector materials, and (d) a motor. The Functional Unit is 1 ESPs manufactured by Baker. Table 2 shows the GHG inventory calculated for ESPs with PMMs and CS.

With these greenhouse gas emissions inventory data, the CCalC₂ 2016 Software shows a calculated carbon footprint value for the Submersible Electric Pump with Normal Induction Motor of 23,436.60 kg CO₂ eq/UF, while the carbon footprint of the product for the Submersible Electric Pump with PMMs and CS showed a value of 18,046.182 kg CO₂ eq/UF. The values showed a reduction of 23% of the Carbon Footprint for the ESPs with the application of new technology.

Data was collected from 12 oil wells and operated by Baker Hughes to date. A total of 18.8% energy reduction is observed by using the PMMs and CS in the ESPs Pump manufactured by Baker Hughes.

Table 2. Greenhouse gas inventory for Electric Submersible Pump with Permanent Magnet Motor and CanSystem.

Parameters	Unit	Raw Material	Manufacturing	Storage	Use
Electric Submersible Pump	kg	656	0	0	0
Electrical energy	kW/h	0	0	0	4.44×10^4
Transportation energy	kW/h	0	1491.66	1491.66	0
Packaging	kg	0	0	0	0

Figure 4 shows the results of the CF with the GHG emissions inventory calculated for the assembly of ESPs with PMMs and CS.

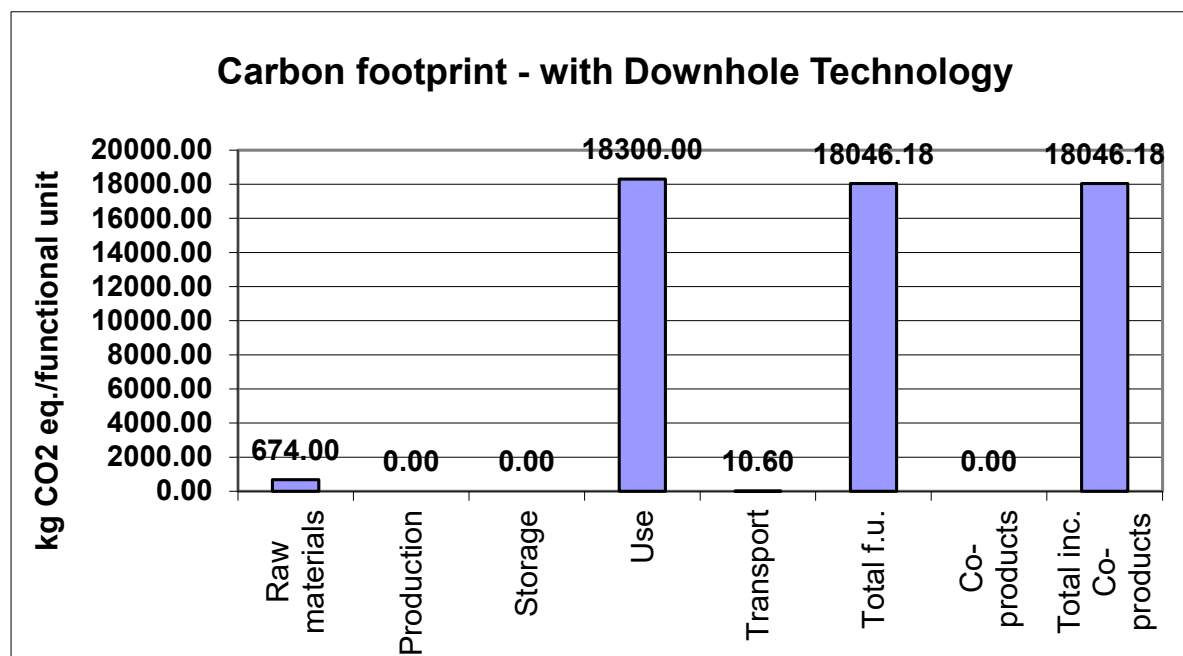


Figure 4. Carbon footprint for the assembly of ESPs with PMM and CS. Adapted from CCalC2 Software.

4. Discussion

Although the results of the application of GHG emissions show a significant decrease, a comprehensive diagnosis should be conducted considering carbon footprint and environmental indicators. Environmental improvement efforts in the oil extraction area are limited to determining control measures only in administrative processes, with most focusing on restrictions on office materials or reducing electricity consumption. No related studies are found, and there is no guidance in PAS 2050 or ISO 14044 defining the LCA map of manufacturing an ESPs. Information regarding the: (a) required inputs, (b) materials, (c) activities, and (d) tasks in the ESPs manufacturing process is restricted and available only to Baker Hughes personnel due to intellectual property rights, making data collection and inventory disclosure for comparison challenges.

The savings in unit costs (USD) and environmental costs would be significant with the application of PMMs since more than 90% of oil wells in Ecuador use artificial lift of oil with ESPs.

5. Conclusions

For LCA in the manufacture of an ESPs with Baker Hughes technology, five stages were determined: (a) raw material, (b) production, (c) distribution, (d) use, and (e) disposal. Fourteen activities related to the LCA in the manufacturing of a Submersible Electric Pump at Baker Hughes were identified, considering the concept: from cradle to grave.

The final GHG inventory for the manufacture of an ESPs with a NIMs show: 656 kg of raw material, 1491.66 kW/h of energy for manufacturing, 1491.66 kW/h for storage, and 5.77×10^4 kW/h for use. For the manufacture of ESPs with PMMs and CS we have: 656 kg of raw material, 1491.66 kW/h of energy for manufacturing, 1491.66 kW/h for storage, and 4.44×10^4 kW/h for use.

The PCF for the ESPs with NIMs is: 23,436.60 kg CO₂eq/UF, while the PCF for the ESPs with PMMs is 18,046.182 kg CO₂eq/UF. This indicates a reduction in the PCF by 18.9% when using the PMMs and CS as a clean technology.

The LCA defined for the manufacture of an ESPs could serve as a baseline for calculating the environmental attenuation of any technology, whether in materials, storage, use or recycling, although only for petroleum types like those taken as reference in the study with an oil gravity range of 788 to 920 kg/m³, gas gravity between 0.65 and 1.276, and separator pressure and temperature of 2.86 MPa and 52 °C.

The application of clean technology using PMMs in the manufacture of ESPs could be a feasible alternative in Ecuador, since, in addition to reducing the PCF, the energy consumption is reduced by 18.19%.

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Data Availability Statement: The data supporting the reported results are on file in the Engineering Department of Baker Hughes Ecuador. The technology mentioned in this research is used in the oil wells operated by Baker Hughes.

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Conflicts of Interest: Authors Juan Córdova-Suárez and Ricardo Teves were employed by the company Baker Hughes. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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