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Environmental and Economic Analyses of TIG, MIG, MAG and SMAW Welding Processes

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Abstract: Metal welding processes, and electric arc welding in particular, constitute a key link in a production chain comprising a large number of companies. This fact, in addition to a growing trend in favour of more in-depth environmental analysis and control of industry, and the need to continue affording due consideration to the economic aspect set the stage for this study. Herein, an environmental and economic analysis is conducted of four types of electric arc welding: TIG welding with and without filler, MIG, MAG, and SMAW welding. Different types of materials are examined such as carbon steel, stainless steel, and aluminium, thus the results generate relevant comparative information on the economic and environmental impacts of choosing one type of welding over another. To this end, an experimental study was carried out: 480 test specimens were welded using different welding technologies. A series of data was collected during the welding process to inform an environmental analysis based on a Life Cycle Analysis and an economic study. The most salient results include that the TIG welding process with filler generated the greatest environmental impact due to its higher consumption of shielding gas. On the other hand, the SMAW process demonstrated the best environmental performance as categories such as Global Warming Potential; CO_2 emissions dropped by 93.29%. A key factor is the final indicator of human health, where, once again, TIG technology had the worst results, in contrast to SMAW technology, wherein impact decreased by 93.08%. On the other hand, the use of TIG technology implies a higher economic cost due to a 61.36% increase in welding time compared to the average welding technology.

Keywords: welding; sustainability; production; weld; economic analysis; environmental analysis

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Citation: González-González, C.; Los Santos-Ortega, J.; Fraile-García, E.; Ferreiro-Cabello, J. Environmental and Economic Analyses of TIG, MIG, MAG and SMAW Welding Processes. *Metals* **2023**, *13*, 1094. https://doi.org/10.3390/met13061094

Academic Editors: Guido Di Bella and Hardy Mohrbacher

Received: 29 April 2023
Revised: 25 May 2023
Accepted: 6 June 2023
Published: 9 June 2023

1. Introduction

The welding industry, which is part of metallurgical industry, has been strongly criticized in recent decades for being a major consumer of raw materials. This has negative effects on the degradation of ecosystems, loss of biodiversity, and water and soil pollution. Additionally, the consumption of huge amounts of energy needed to transform these raw materials into new metals and alloys. Emitting greenhouse gases, as well as generating waste and fumes that significantly affect human health. This contributes to the global problem of climate change. In addition to these environmental impacts, there is also the economic importance it brings to society. In some countries, such as Spain, this sector represents 40% of the country's industrial production [1]. This sector has been influenced by the new guidelines of the global sustainable development targets proposed by the United Nations [2]. These propose the transition of industries towards sustainable production. In the case of the welding industry and given its importance, this is a new challenge. This is an industry in which legislation on environmental, sustainability, and production issues are practically non-existent. Given this current situation in the sector, it is up to society to develop new knowledge and techniques that will enable the objectives of sustainable development to be achieved. For instance, through knowledge of the environmental impacts associated with the various activities carried out in this industry. With the aim of being able to mitigate or reduce them. Additionally, through the efficient use and consumption of resources. However, not only natural resources and raw materials, but also economic resources.

In Spain, metal welding jobs are of notable significance, as it has been determined that 25,597 people work in this profession [3] in the field of structural welding [4]. Metal welding processes have different typologies and specifications that depend on a multitude of factors and criteria. Some of these factors are the understanding of the internal microstructure of the weld. For example, the research by Shen et al., where they characterise the internal microstructure. As well as the mechanical properties of the weld made using Gas Metal Arc Welding (GMAW) technology. Using a filler material of 308 stainless steel [5]. In addition to other related studies [6,7]. Other criteria to be highlighted are resistance both to stress and to the conditions to which welds may be subjected, aesthetic criteria depending on the applications and final uses of the products to be welded, environmental criteria in terms of consumption and inputs, and, of key importance, economic criteria. All these factors, along with the existence of a wide range of different types of welding, and bearing in mind that welding cannot always be performed in a workshop but rather is carried out on site or on production lines [8], demonstrate that welding is not a straightforward endeavour and constitutes a very interesting field of research.

Furthermore, thanks to the recent implementation of Industry 4.0, which involves the digitisation of production processes by analysing vast swathes of data, along with the integration of technologies and automation of manufacturing, it is possible to obtain real-time information that informs and empowers live decision-making [9]. The industry evolution towards automation currently underway is also driven by increased customer expectations in terms of environmental awareness and carbon footprint reduction [10]. However, putting these new technologies and automation into practice in small- and medium-sized enterprises requires financial investment and resources that not all companies have. This fact represents a drawback for many businesses. According to Gonzalez and Vanti, in order to foster sustainable economic growth in Spain, investment in R&D, innovation, digitisation, and digital transformation must be bolstered [11].

Welding is an indispensable manufacturing process that involves joining two or three metals (similar or dissimilar) by heating them to a molten state, which allows them to be joined together and solidify into a fixed joint [12]. The use of welding processes is widespread in sectors such as automotive [13], railway, shipbuilding [14,15], aerospace [16,17], and civil construction [18,19]. The most widely used welding processes are Shielded Metal Arc Welding (SMAW); Gas Metal Arc Welding (GMAW), which notably include Metal Inert Gas (MIG) and Metal Active Gas (MAG); TIG, also called Gas Tungsten Arc Welding (GTAW); Ultrasonic Welding (USW); Laser-Beam Welding (LBW); Friction Stir Welding (FSW); and Electron Beam Welding (EBW) [20]. MIG/MAG, TIG, and SMAW processes are the most versatile, economical, generic, and commonly used in the majority of the aforementioned sectors; thus, these are evaluated in the present study [21,22].

Working with the foundation of the various welding technologies available, current research focuses on examining specific welding cases in order to obtain the mechanical, thermal, and durability characteristics of a particular type of welding technology. For example, Sattarpanah et al. used finite element analysis to evaluate the thermal behaviour of TIG-welded stainless steels. The relationship between welding speed, bead width, and penetration depth is evident. As an increase in current and decrease in welding speed result in the weld bead width increasing, as well as the depth of penetration. Due to the fact that the input energy (derived from the increased current) is increased and the energy that it transmitted to the material. Therefore, the molten volume of material increases [23]. Another case study was from Jun et al., which examined the feasibility of welding armour steel plates with GMAW and Flux Cored Arc Welding (FCAW) technology [13]. On the other hand, other research evaluated the filler material used in welding. For instance, Liu et al. assessed welding for a fuel tank with filler materials of different chemical compositions [16].

Therefore, at present, the field of research dedicated to welding is centred around evaluating specific cases so as to draw conclusions and improve the process. However, several research initiatives addressing environmental and economic sustainability have already come about in this area.

A study by Epping and Zhang evaluated the transfer from SMAW welding technology to robotic welding with GMAW technology for companies. They carried an economic, social, and environmental analysis. The results showed that GMAW welding led to a cost reduction of 42.51% in the case study. Likewise, in environmental categories such as the consumption of fossil fuels, it was lower due to the reduction in the manufacture of the parts. Finally, in social impacts such as the health and safety of workers, there were benefits: with robotic welding, the distance between the worker and the hazardous materials involved in welding increased. It also reduced the amount of fumes generated by the welding process. Specially, a decrease of 68.97% [24].

Another study by Sarkar et al. indicated that TIG welding of 1 mm aluminium sheets had a higher environmental impact than MIG welding, around 1.3 times higher on average, but this increase could be ameliorated by implementing automation techniques in the TIG process [25]. Research by Favi et al. revealed that the environmental loads of SMAW and GTAW were greater than those of GMAW processes and that, in addition, the variables intensity, voltage, and operator skill influence SMAW and GTAW processes to a greater extent than GMAW processes [26]. On the other hand, a study by Demir and Furlan analysed the impacts and environmental viability of traditional welding processes such as SMAW, GTAW, and GMAW as compared to modern processes such as LBW, revealing that LBW processes performed better than traditional methods for small thicknesses in aluminium and that LBW techniques required fewer subsequent finishing and cleaning operations [27]. A study by Afzal et al. examined the environmental impact of GTAW welding processes compared to LBW processes, using experiments on AISI-304 stainless steel, and concluded that LBW processes had lower impacts, even compared those GTAW processes without material input, due to many factors, including speed [28].

In addition to the environmental aspects, one of the most important factors when designing products and planning welding processes is cutting manufacturing costs. To achieve this cost reduction, process optimization is used. Process optimizations consist of studying the process, including the variables involved (material, energy, staff), and determining how these can be reduced without losing minimum product quality. One of the most popular options is the automation of welding. With the use of robotized welding, parameters such as wire feed speed, amperage, and shielding gas glow rate can be controlled more efficiently. These costs are often underestimated. On the other hand, competent preventive maintenance of the equipment involved in welding can considerably reduce downtime due to failures. This fact has already been highlighted by other studies for the past two decades [29]. The economic significance of welding processes in Europe and their economic impact on European industry has been notable for some years now [30]. A decade ago, the term "sustainable manufacturing" was defined in the USA as the creation of manufactured products using processes that minimise negative environmental impacts; conserve energy and natural resources; are safe for employees, communities, and consumers; and are economically sound [31]. Some studies have analysed the economic impact of a welding process and searched for methods or tools to reduce costs [32]. Methods have also been developed to support the selection of the most suitable welding process based on economic criteria [33–35].

However, the actual experience of carrying out welding processes for a product in a company points to different selection criteria. These criteria help the company to determine which welding technology is most suitable. The selection criteria must satisfy the customer's requirements. These requirements are usually of an aesthetic and technical nature. To this end, the company, depending on its material and human resources, determines the means necessary to carry out the welding work. Thus, the decisions to be made are complex and involve more specific factors. To facilitate this decision-making process, complex integrated decision-making systems are available on the market; they are parameterised and have different variables depending on pre-established requirements [36]. However, it is not feasible to implement such selection models in small- and medium-sized companies.

Therefore, this study aims to obtain economic and environmental knowledge about the most widely used welding processes. To this end, the economic costs of each type of welding technology were examined by measuring the most characteristic parameters (consumption of filler material, electrical energy, protective gas). These indicate the total economic cost of producing a weld depending on the technology. In addition, an environmental analysis was carried out to determine which welding technologies had the greatest impact on the environment and on human health. This research contributes new data on the economic and environmental costs generated by using one welding technology or another, and it does not focus solely on a specific case study, as most recent research has tended to do.

2. Materials and Methods

This section discusses the methodology used to conduct the various case studies. It is divided into the mechanical methodology, which explains how the test specimens were created, and the environmental methodology wherein the Life Cycle Analysis (LCA) was applied, and, finally, the economic aspect is addressed. These different analyses serve to characterise the various case studies comprising this study.

2.1. Mechanical Methodology

The mechanical methodology explains how twelve welding case studies using different technologies were performed. To this end, an experiment was carried out in which test specimens made of different materials underwent different welding processes.

2.1.1. Sheet Materials

Three sheet materials were used: two steels, one carbon steel, one stainless steel, and one aluminium. The first was the structural carbon steel S275 that complied with the European standard EN 10025:2004 [37]; this was a common carbon structural steel with a yield strength of 275 MPa, and it was supplied by the supplier Arcelor Mittal [38]. The second was AISI-304L stainless steel, which was a general purpose austenitic stainless steel, especially non-magnetic in the annealed state, and could only be cold hardened with a minimum of 10.5% chromium. It was supplied by the supplier Acerinox Europa [39]. Finally, AW-5754-H111 aluminium sheets were an alloy with a high mechanical strength of 200 MPa; they were very easily welded by conventional methods and suitable for anodising or protection treatments. They were supplied by Slim Fusina Rolling [40]. Figure 1 shows the sheets utilised in the case studies. All activities related to the experiment were carried out in a workshop dedicated to boiler making and welding activities.

The test specimens were designed with the same geometry in all the case studies; only the material varied. The dimensions were 100 mm × 50 mm with a thickness of 5 mm for the vertical specimens. These were fitted onto a base of the same material for all case studies, with the following dimensions: 500 mm × 200 mm and 5 mm thick. All the pieces were laser cut in the workshop from sheets measuring 3000 mm × 1500 mm, using fibre laser technology on a Trumpf Trulaser 3030 fibre model (TRUMPF, Madrid, Spain). Figure 2 shows the vertical specimens on top of the base to which they were later welded.

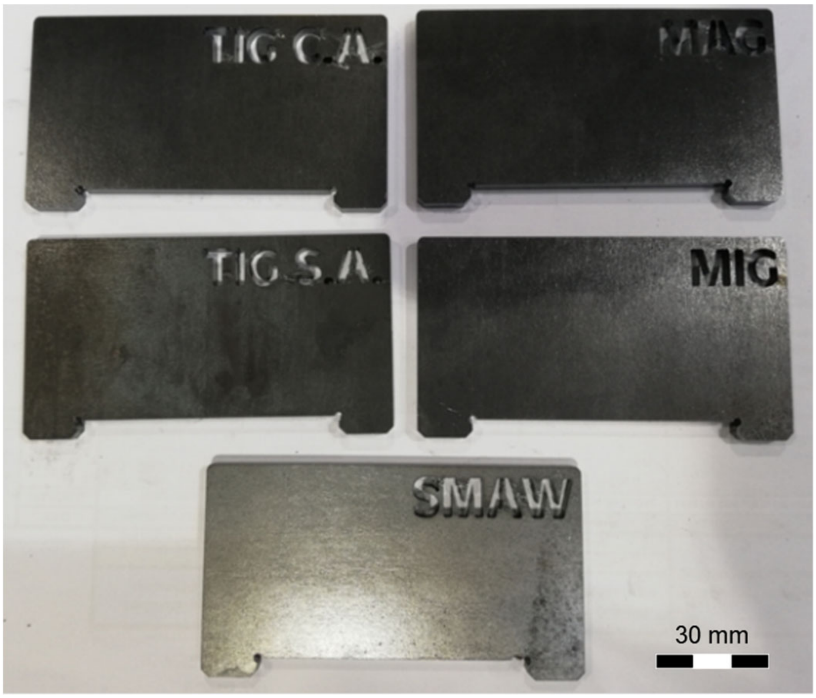


Figure 1. Carbon steel test pieces.

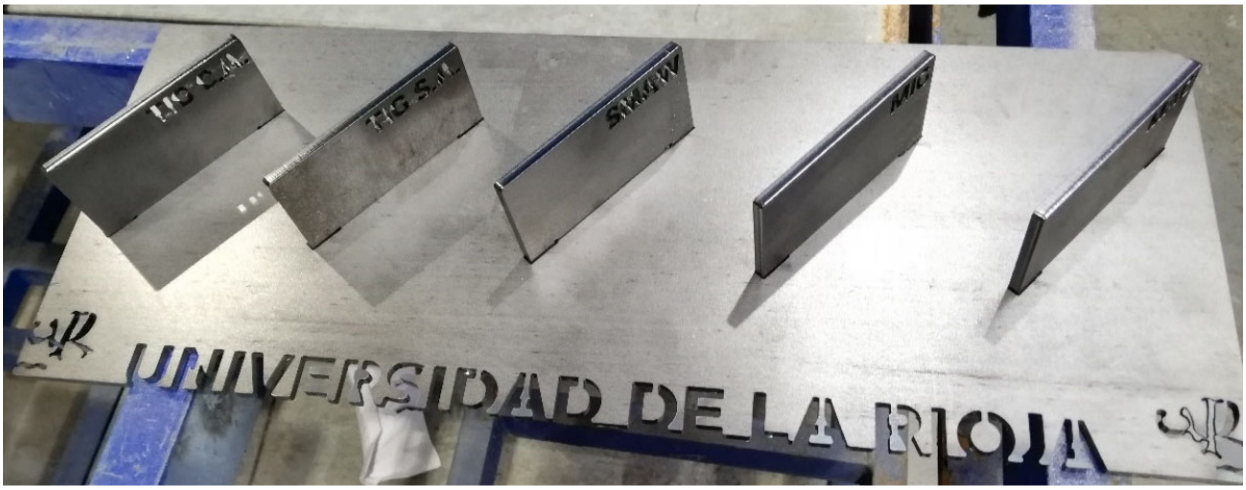


Figure 2. Base and test samples set.

Five types of welding were used: TIG welding with filler material, TIG welding without filler material, MIG welding, MAG welding, and, finally, SMAW welding. For some materials, it was decided not to study all the types of welding due to technical unfeasibility or production criteria. Thus, in the case of carbon steel, all five welding processes were analysed. For stainless steel, SMAW welding was eliminated since it was no longer in use in industrial boiler making. Additionally, for aluminium, SMAW and MAG processes were not included in the study, as their use was also declining. This decision was justified because the welding processes with active shielding gases had negative results. Table 1 lays out which case studies used which materials and welding processes.

Table 1. Combination of materials and welding processes: case studies.

Type of Welding	Carbon Steel S275	Stainless Steel AISI-304L	Aluminium AW-5754-H11
TIG without filler	Case 1	Case 6	Case 10
TIG with filler	Case 2	Case 7	Case 11
MIG	Case 3	Case 8	Case 12
MAG	Case 4	Case 9	-
SMAW	Case 5	-	-

With the aim of unifying welding criteria across the different types of processes used in all the case studies, a fillet weld was made, specifically, a corner fillet, on both sides of the test piece, continuously and horizontally, along the 100 mm of each specimen with a throat of 4 mm. The edges of the parts to be joined did not undergo any preparation; the bead penetration was exclusively due to fusion generated during the process.

2.1.2. Filler Material

The filler material was used in nine case studies, with the exception of the case studies where the TIG process was applied without filler material. The following seven different filler materials were used, all of them from Praxair (Viana, Spain) [41]: the PROSTAR M86 (AWS 5.18 ER 70S-6) wire for MIG/MAG welding of high-quality carbon steels, measuring 1.2 mm in diameter; PROSTAR material M-309L (AWS 5.9 ER 309LSi) with a diameter of 1.2 mm, a stainless-steel wire of type 23-713 with low carbon content used for MIG/MAG welding of dissimilar steels; PROSTAR M-1050 with a diameter of 1 mm, an aluminium wire of type M-1050 used for MIG welding of aluminium; PROSTAR T-86 (AWS 5.18 ER 70s-6) with a diameter of 2.4 mm, a copper-plated carbon steel rod used for TIG welding of carbon steels; PROSTAR material T-308L (AWS 5.9 ER 308L) with a diameter of 2 mm, a low carbon stainless steel rod for TIG welding of 18/8 stainless steels; PROSTAR T-1050 (AWS 5.10 ER 1100) with a diameter of 3 mm, a pure aluminium rod used for TIG welding of aluminium; and, finally, PROSTAR B-70 (AWS 5.1 E 7018-1) with a diameter of 4 mm, a basic coating electrode with notable mechanical properties for universal use, which was used in case study 5. Table 2 lists the filler materials selected according to the test piece material and the type of welding.

Table 2. Distribution of filler materials.

Type of Welding	Carbon Steel S275	Stainless Steel AISI-304L	Aluminium AW-5754-H11
TIG with filler	PROSTAR T-86	PROSTAR T-308L	PROSTAR T-1050
TIG without filler	-	-	-
MIG	PROSTAR M86	PROSTAR M-309L	PROSTAR M-1050
MAG	PROSTAR M86	PROSTAR M-309L	-
SMAW	PROSTAR B-70	-	-

2.1.3. Welding Equipment

For the experiment, three welding units were used, all of them from the manufacturer FRONIUS (Madrid, Spain) [42], along with the different power ranges from 170 to 500 A, namely, the Fronius–TransTIg 1750 Plus, which is a TIG-DC power source with an output of 170 A; the Fronius–TrasPulsSynergic 270i C; and the Fronius–Magic Wave 2600, which is an AC/DC TIG power source used especially for aluminium applications.

Once the test pieces had been laser cut, the experiment was carried out in a workshop designated for metal welding and boiler making on the University of La Rioja campus (Logroño, Spain). Twenty sets of specimens of each of the materials were welded together. All the tests were performed with the same welder and under the same conditions, obtain-ing a sample of 480 welding seams distributed among the twelve case studies. The welding process is captured in Figure 3.

Figure 3. Experiment underway in workshop.

2.1.4. Measurement of Variables

This study limits its scope to the consumption generated during the different welding processes, excluding inputs and waste. Therefore, the parameters measured during the experiment were: welding times in each case study, welding voltage and intensity, the flow rate of the shielding gas (not relevant for all case studies), and filler material (not all the case studies used filler material). Thus, the three consumptions focused on in this study (see Table 3) were obtained: electrical energy, filler material, and shielding gas. The welding times were controlled in situ with a stopwatch. In the fastest cases, times of around 42 s per test piece were achieved, and, in the slowest cases, the times were around 144 s. Electricity consumption was calculated by taking the current and voltage values at which the welding machine was regulated, along with the amount of time in use, thus calculating the consumption in kWh. The electrical energy consumption in more unfavourable processes was 0.31 kWh for each test piece and 0.032 kWh per test piece in more efficient processes. As for the consumption of shielding gas, it was calculated by measuring the flow rate of gas supplied along with the supply or welding time.

Table 3. Ranges of measured variables.

Variable Measured in Tests	Interval
Electricity consumption (kWh)	0.032–0.31
Execution time (s)	42–144

2.2. *Environmental Methodology*

For the environmental part of the study, an LCA was completed. This methodology quantifies the environmental impacts of a product, process, or system throughout its life cycle.

2.2.1. Scope and Goals

The objective of this environmental assessment was to determine the environmental impacts associated with welding operations using various technologies. Thus, it would be possible to establish which welding technology had less environmental impact while also quantifying its impacts. The scope of the LCA was from cradle to gate, as the welding production process was where the highest energy and material consumption occurred. Figure 4 shows the system boundaries of the LCA study.

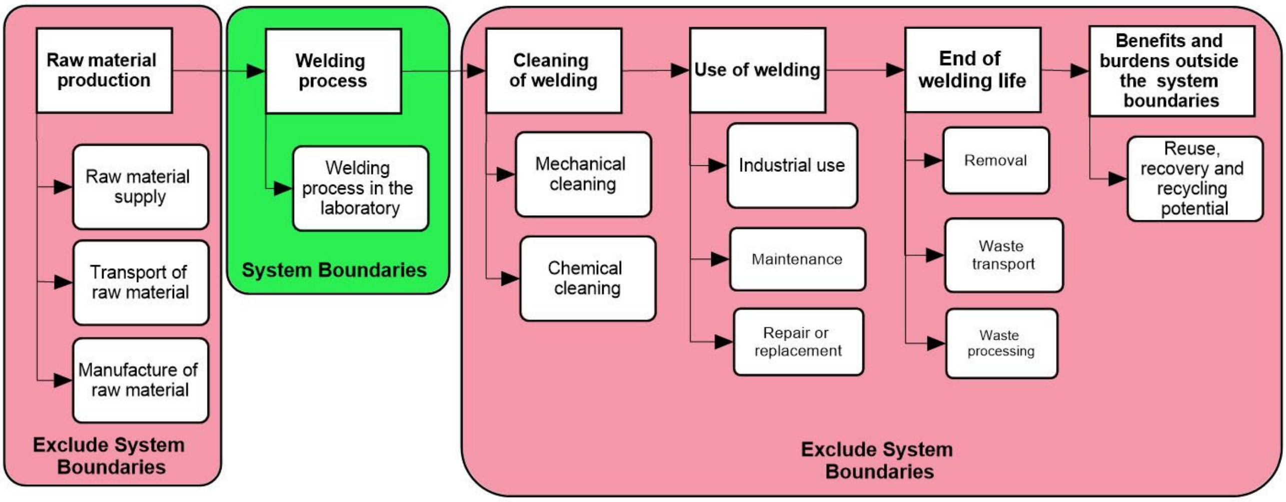


Figure 4. Scope of this study's LCA.

2.2.2. Functional Unit

The functional unit (FU) designated in this study was a continuous horizontal weld bead of 100 mm in length and a 4 mm throat. Table 4 shows the different functional units of the various case studies.

Table 4. Functional units according to case study.

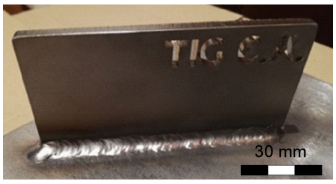
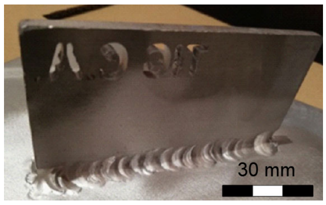
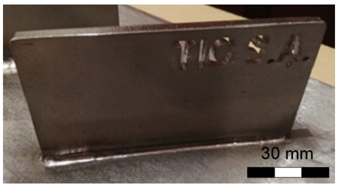
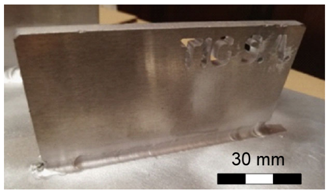
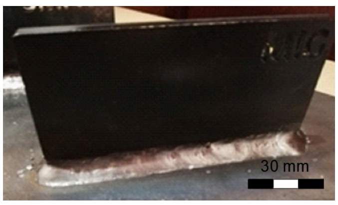
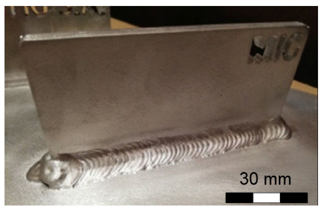
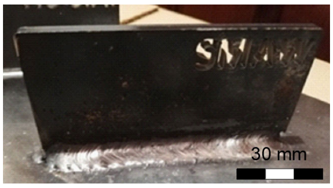
Type of Welding	Carbon Steel S275	Stainless Steel AISI-304L	Aluminium AW-5754-H11
TIG with filler			
TIG without filler			
MIG			
MAG			

Table 4. *Cont.*

Type of Welding	Carbon Steel S275	Stainless Steel AISI-304L	Aluminium AW-5754-H11
SMAW			

2.2.3. Life Cycle Inventory

The Life Cycle Inventory (LCI) gathered all the quantities of energy and matter involved in the welding process for each case study. The data were obtained from the measurements taken in the laboratory. For the filler materials, their chemical composition data sheets were consulted. The LCA was modelled in the SimaPro 9.4 software (PRé, Amersfoort, The Netherlands) [43]. Of all available databases, the Ecoinvent v.3 database [44] and the ELCDs (European Life Cycle Databases) were used. Table 5 lists the amounts of energy as well as the materials used to produce the FU in each case study.

Table 5. LCI for each case study.

Inventory	Case Study											
	1	2	3	4	5	6	7	8	9	10	11	12
Electric Energy (kWh)	0.032	0.056	0.046	0.061	0.313	0.032	0.051	0.04	0.041	0.016	0.049	0.037
Argon (g)	386.97	610.44	185.10	181.13	-	171.88	330.54	174.21	127.68	227.73	331.03	146.72
CO_2 (g)	-	-	-	31.96	-	-	-	-	22.53	-	-	-
Carbon (g)	-	0.018	0.006	0.006	-	-	0.03	0.002	0.002	-	-	-
Manganese (g)	-	0.264	0.086	0.084	0.402	-	0.181	0.107	0.109	-	0.002	0.001
Silicon (g)	-	0.155	0.050	0.049	-	-	0.052	0.050	0.051	-	0.020	0.008
Sulphur (g)	-	0.005	0.001	0.001	-	-	0.002	0.001	0.001	-	-	-
Phosphorus (g)	-	0.005	0.001	0.001	-	-	0.003	0.002	0.002	-	-	-
Copper (g)	-	0.064	0.021	0.02	0.060	-	0.052	0.030	0.031	-	0.004	0.002
Nickel (g)	-	0.027	0.009	0.009	0.060	-	1.037	0.792	0.81	-	-	-
Chrome (g)	-	0.027	0.009	0.009	0.040	-	2.095	1.461	1.496	-	-	-
Molybdenum (g)	-	0.027	0.009	0.009	0.040	-	0.052	0.030	0.031	-	-	-
Vanadium (g)	-	0.005	0.002	0.002	0.010	-	-	-	-	-	-	-
Aluminium (g)	-	0.004	0.001	0.001	-	-	-	-	-	-	20.006	7.679
Titanium (g)	-	0.027	0.009	0.009	-	-	-	-	-	-	0.002	0.001
Iron (g)	-	17.578	5.725	5.596	19.478	-	6.894	3.614	3.698	-	0.050	0.019
Beryllium (g)	-	-	-	-	-	-	-	-	-	-	0.006	0.002
Zinc (g)	-	-	-	-	-	-	-	-	-	-	0.008	0.003
Magnesium (g)	-	-	-	-	-	-	-	-	-	-	0.004	0.002

2.2.4. Life Cycle Assessment

SimaPro9.4 software was used to perform the LCA, and the EPD 2018 methodology was applied to calculate the environmental impacts. This methodology was used to create Environmental Product Declarations (EPD). It is also employed in industry to obtain product-specific EPDs. Thus, the environmental impacts associated with a specific product are regulated and controlled. These EPDs compile information on the environmental impacts of a product throughout its life cycle according to the ISO14025 standard [45]. The impact categories of this methodology are shown in Table 6.

During the welding process, harmful gases are released into the work environment where welding is taking place. These emissions of particles and elements can lead to health problems for the workers. Therefore, apart from the EPD 2018 methodology, the ReCiPe 2016 (H) methodology was applied herein, as it incorporated impact categories directly related to workers' health. This was the case of the final indicator called Human Health, which was quantified by the unit DALY (Disability Adjusted Life Years), which encapsulated the number of years of life lost due to illness, disability, or premature death. This assessment methodology incorporated a total of 22 intermediate indicators. These were used to assess the worst-case study and compare them with the results of the EPD

2018 methodology. However, in order to understand how the twelve cases studies affected human health, their final indicators (Human Health, Ecosystems, and Resources) were consulted.

Table 6. Impact categories of EPD 2018 methodology.

Impact Categories	Unit
Acidification	kg SO_2 eq
Eutrophication	kg PO_4 eq
Global Warming Potential (GWP)	kg CO_2 eq
Photochemical oxidation	kg NMVOC
Abiotic depletion, elements	kg Sb eq
Abiotic depletion, fossil fuels (ADFF)	MJ
Water scarcity	m^3 eq
Ozone layer depletion	kg CFC-11eq

2.3. Economic Methodology

The costs of the different electric arc welding processes were analysed comparatively. This made it possible to create an economic comparison and relate it to the environmental comparison outlined in the previous section, thereby generating a two-sided criterion (economic and environmental) to select one type of welding or another.

The direct costs of the welding processes used included the welding equipment. In this case, three different types of Fronius equipment were utilised. A cost/time ratio was also generated, establishing 3600 welding hours per piece of equipment as the useful life. Thus, the time employed and cost of each case study were calculated, as shown in Table 7.

Table 7. Cost of welding equipment.

Welding Equipment	Equipment Cost (€)	Ratio (€/seg)
Fronius–TransTIG 1750 Puls	1800	1.3889×10^{-4}
Fronius–TransPulsSynergic 270i C	2300	$1.775 \times \cdot 10^{-4}$
Fronius–Magic Wave 2600	3400	$2.6234 \cdot \times 10^{-4}$

Table 8 lists the costs derived from energy, materials, and labour for the case studies. The energy consumption was calculated for each case study in kWh to determine the cost of energy consumption depending on the type of machine. To calculate the cost per kWh, the energy company ENDESA was consulted. ENDESA established an average value of 11.99 cents €/kWh.

Table 8. Costs derived from energy, materials, and labour, according to case study.

Case Study	Energy Cost		Filler Material Cost		Shielding Gas Cost		Labour Cost	
	Electricity (kWh)	By FU (cent€)	Length (mm)	By FU (cent€)	Volume (l)	By FU (cent€)	Execution Time (seg)	By FU (cent€)
1	0.0325	0.389	-	-	24.00	55.20	90	0.8750
2	0.0562	0.674	512	2.533	37.87	26.40	142	1.3805
3	0.0457	0.548	652	3.232	11.48	34.34	53	0.5153
4	0.0612	0.734	667	3.160	13.21	47.15	61	0.5931
5	0.3125	3.747	521	11.234	-	-	82	0.7972
6	0.0322	0.386	-	-	10.66	24.51	64	0.6222
7	0.0508	0.610	420	2.462	20.50	24.90	123	11.958
8	0.0396	0.475	685	3.677	10.83	24.20	50	0.4861
9	0.0405	0.486	701	3.763	9.31	32.49	43	0.4181
10	0.0165	0.198	-	-	14.13	47.21	53	0.5153
11	0.0488	0.585	318	1.629	20.53	20.93	77	0.7486
12	0.0369	0.442	868	4.361	9.10	55.20	42	0.4083

The next cost derived from the consumption of filler material. The cost of the filler material depended mainly on several variables. These were the FU execution time, the consumption of shielding gas, and, finally, the type of material to be welded. Excessive welding time could lead to excessive consumption of filler material and even to a detective weld bead. In order to avoid significant differences and to optimise the process, the tests were carried out by a professional welder. In this way, with the welder's experience in this field. It was possible to obtain more optimised and accurate results in the welding industry. If the tests were carried out by an unqualified person, this could lead to defective welding beads and variable results that were out of line with reality. In addition to this, it was checked that the welding machines were calibrated, so that they did not show erroneous voltage and current intensity variables. It was also checked that the filler material was in proper storage conditions and had not suffered any type of deterioration.

To calculate this cost, the consumption of the filler material was obtained in millimetres (mm). This input material could be rod, wire, or electrode. The cost of purchasing the filler material was also determined, which varied between 4.94 and 21.56 (cents €/m), thus, the economic cost of using the filler material could be calculated. An extremely significant consumer of resources in electric arc welding processes is the shielding gas (argon or a mixture of argon and CO_2). The shielding gas consumed in 11 out of the 12 cases of study was obtained (only 11 in the case of SMAW because the shielding gas arose in situ by chemical reaction at the start of welding and, therefore, did not need to be supplied) and used to calculate the cost ratio of the shielding gas for the FU of each case study, bearing in mind the cost of the shielding gas, which ranged between 2.3 and 2.6 (cents €/l).

One of the most noticeable costs for any company that includes welding processes in its production chain is labour. In addition to the cost of the time spent by the operator doing the welding, this time can have repercussions in terms of delays in deliveries, reduction in response capacity, penalties for failure to meet deadlines, etc. This is why examining the times employed in the different processes and comparing them is of vital importance. A cost of 35 €/h of work was established, which, along with the times measured in the experimental work, enabled us to calculate the cost derived from labour per/in the FU of each case study.

3. Results and Discussion

The results are divided into environmental and economic. Firstly, the results of the twelve case studies according to the environmental methodologies EPD and ReCiPe 2016 are explained in general terms. Subsequently, the case study with the worst environmental impact is analysed. The economic results and their distribution are then analysed. Additionally, and lastly, the combination of the economic cost of the FU with selected impact categories is discussed. These categories are GWP and Human Health, as both impacts are easily comprehended by the general public. This combination of economic costs and environmental results allows us to visually illustrate which technology and case study had the poorest performance.

3.1. Environmental Results

3.1.1. General Comparison

Figure 5 displays the environmental results obtained from the LCA according to case study and impact category, based on the EPD 2018 methodology. As can be observed, case two had the highest impact across all the categories except for the abiotic depletion elements category, in which case seven had the greatest impact. Regarding welding technology, TIG had the worst environmental results, followed by MIG and MAG. Meanwhile, SMAW technology performed the best in environmental terms.

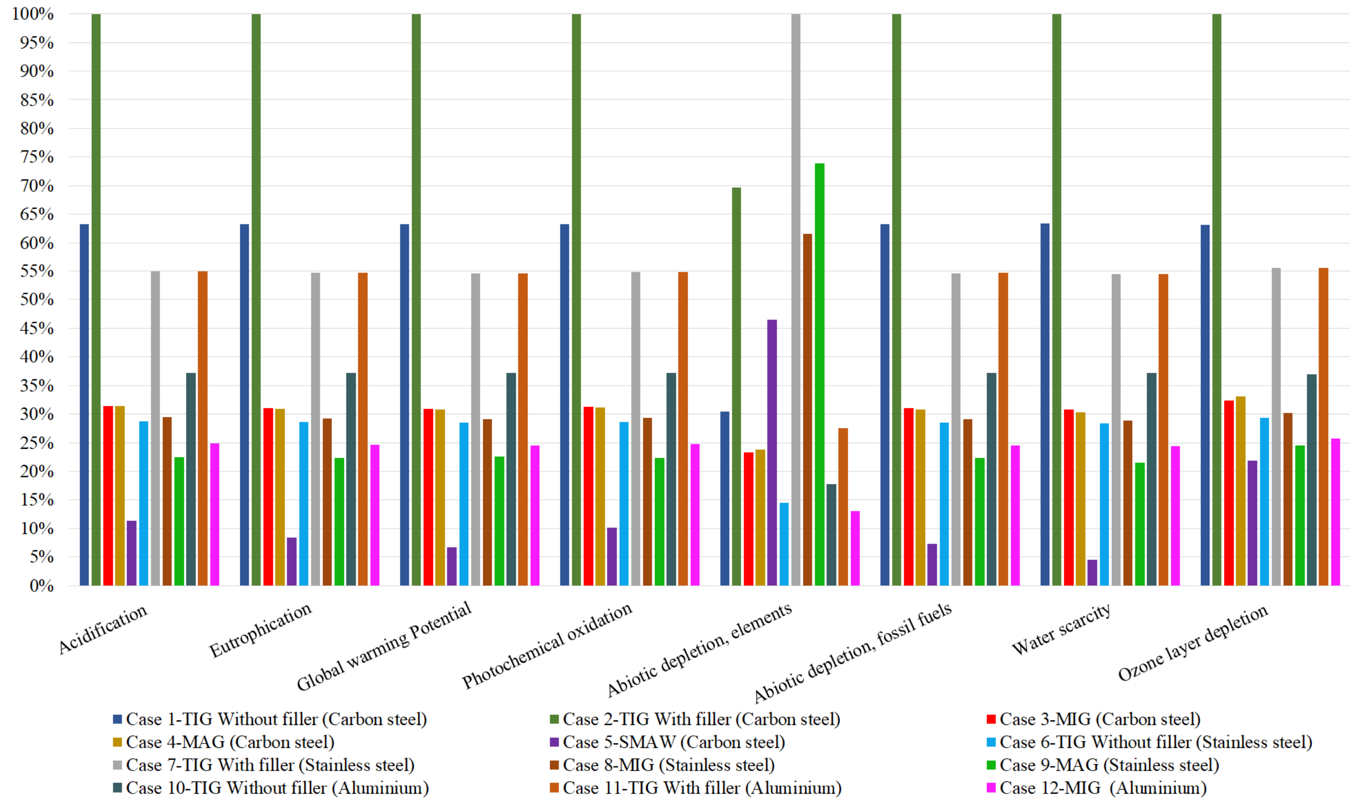


Figure 5. LCA results by impact category and case study.

Using TIG technology implies that more shielding gas, such as argon, is consumed than compared to other technologies, such as MIG or MAG. These differences in the consumption of shielding gas during the FU production process translate into a series of impacts. This is because argon undergoes a manufacturing process in which raw materials and energy are consumed before being consumed in the production process. Cases two and one consumed the highest levels of protective gas (see Table 5); therefore, categories such as Ozone Layer Depletion and GWP had the highest impacts for these cases. A notable difference existed in the GWP category between case two (TIG welding of carbon steel with filler) and case five (SMAW welding of carbon steel): there was a 93.29% increase in CO_2 emissions, which translated into an increase in emissions of 1.34 kg of CO_2 for each FU manufactured. The ADFF category was also remarkable, as there was, again, an increase in impact of 92.73% between cases two and five, which was equivalent to consuming 14.46 MJ for each FU. It could, therefore, be concluded that using shielding gas generated worse environmental results, and the greater the amount used the worse the results. Therefore, case five offered the best environmental results, as its impact was derived exclusively from electrical energy consumption.

Now that the results of the EPD 2018 methodology have been addressed, the final indicators (Human Health, Ecosystems, and Resources) of the ReCiPe 2016 methodology are illustrated in Figure 6, wherein a single weighting and scoring process was applied. This scoring assigns a weight to indicate the relative severity of an impact. Thus, each impact category is designated a certain level of priority, and this, in turn, is assigned to the final indicator. This step, which is an optional feature of the LCA methodology, allows the final indicators to be compared with each other. In this study, the goal was to determine which of the welding cases studied had the greatest impact on human health, ecosystems, or resources. These results are measured in millipoints (mPt), and the sum of all the mPt obtained for each final indicator is the so-called single score for each case study.

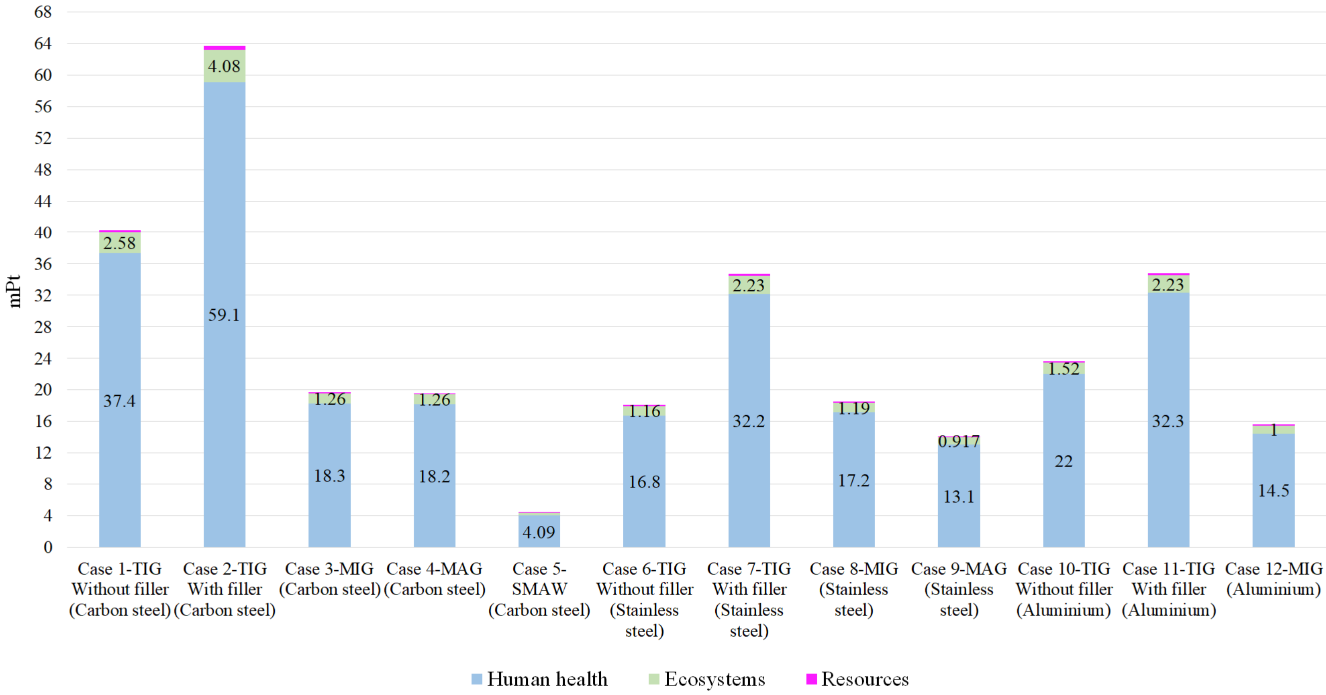


Figure 6. Final indicator results of case studies according to ReCiPe 2016 methodology.

As can be observed, regardless of the welding technology used, the foremost impact indicator affected was human health, with an average value of 23.76 mPt, followed by the ecosystems indicator with 1.64 mPt, and, lastly, the resources indicator, with an average score of just 0.19 mPt. It can, therefore, be affirmed that the welding processes affected the impact categories that comprised the final indicator of human health to the greatest extent. Within each case study, as noted before, case two (TIG welding with filler) was the highest scoring case, with a value of 63.64 mPt, followed by case one (TIG welding without filler) with 40.27 mPt, whereas case five (SMAW welding) was the lowest scoring case with 4.43 mPt. Finally, if the scores were compared according to the welding technologies assessed, the following trend emerged: TIG welding had a score of 35.86 mPt, MIG welding 17.95 mPt, MAG welding 16.87 mPt, and, as mentioned above, SMAW welding 4.43 mPt.

3.1.2. Case Two: TIG with Filler Material

Figure 7 shows the specific distribution of case study two, which obtained the worst environmental results; this was the TIG process using carbon steel. The components of the FU are indicated by different colours: electrical energy, filler material (herein referred to as the bead chemical composition to group together various components and facilitate understanding of the graph), and shielding gas. It could be observed that the production of shielding gas, in this case argon, constituted the largest percentages in all the impact categories. This was because the gas was not obtained naturally but rather involved a prior manufacturing process to synthesise it and store it in a tank for later distribution. Therefore, all the energy consumption and transport associated with shielding gas production were clearly reflected in this analysis. The chemical composition of the weld bead only had a significant impact percentage in the category of abiotic depletion elements, where it reached a value of 30.62%. This impact could be explained by the fact that the weld bead contained a total of 13 chemical elements, with iron being the most predominant (see Table 5). Lastly, the energy consumption of electricity had an average impact value of 2.11%, due to the fact that electricity consumption was not excessive for the FU and specifically for case study two, where, as TIG technology was used, it had the lowest electricity consumption, unlike other technologies such as MIG, MAG, and SMAW. In these technologies, electricity consumption did increase in terms of impact.

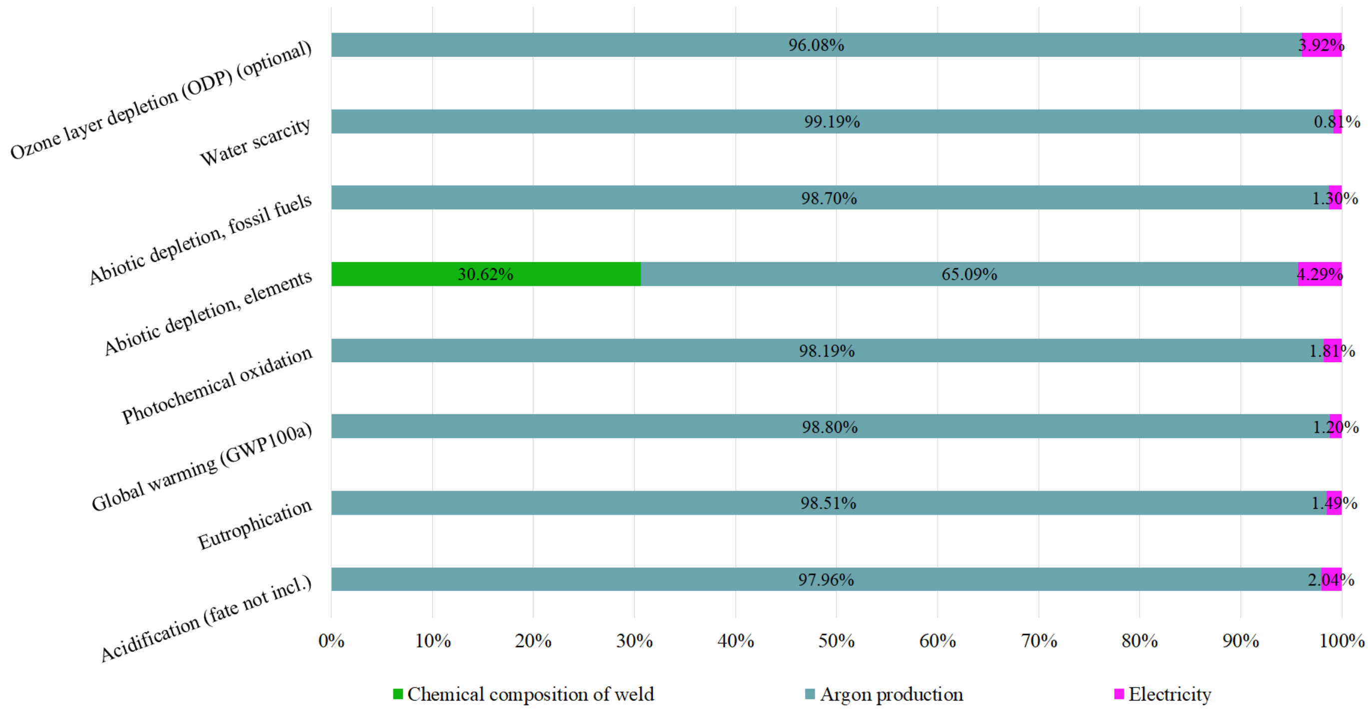


Figure 7. Environmental impacts of case study two, according to EPD 2018 methodology.

Continuing with the environmental results, Figure 8 shows the assessment of case two (TIG welding with filler) according to the ReCiPe 2016 methodology and its intermediate indicators.

As can be observed, this environmental methodology had a total of 22 impact categories reflecting its intermediate indicators. These categories had the benefit of determining the impacts of a specific, concrete case study. Let it be noted that this analysis showed that the production of argon protective gas generated the greatest environmental impacts, as in the previous analysis, with an average contribution to each impact category of 94.75%. This effect was even more significant in certain categories such as water consumption and terrestrial ecosystem, constituting 99.82% of the impact. On the other hand, the chemical composition of the weld bead had no effect on the impact categories evaluated, with the exception of the mineral resource scarcity category, wherein its impact was 84.45%. Finally, the third element studied in the welding process was electricity, with an average impact of 1.41%. This rose to a value of 5.27% in the ionizing radiation category. This increase was due to the impacts derived from transporting electrical energy in high-voltage lines. The current flow caused the air in contact with the lines to ionise.

3.2. Economic Results

Figure 9 depicts the averages of the various economic variables associated with the FU. It can be observed that the most significant cost in the welding process is labour, constituting 66.132% of the costs associated with the production of the FU. This high percentage can be explained by the fact that the FU involves a manual welding process. In addition, the welding execution time by the worker is different for each case analysed. For instance, it is observed that the average execution time is 73.33 s with a standard deviation $\sigma = 31.71$ s. This means that for some technologies this economic item makes a greater contribution, as is the case with TIG technology. Additionally, in other cases, it is not as relevant as in MIG technology. It should be noted that the case studies were supervised in order to correctly quantify the execution times. In this way, it was possible to have supervised and controlled times. In addition to checking that the tests were decent and did not lead to defective results. Another cost with a high impact is the protective gas, which accounts for 30.346% of FU costs. Its presence is essential for some welding processes, and its price is quite elevated because as a hazardous product, its transport and supply require high pressure. As a result, this element is in second place among the costs with the greatest impact. It should be noted that the sum of the cost of labour and shielding gas account for almost the total economic cost of the FU, with 96.478%. The remaining 3.522% is divided into input materials, with 2.787%. The cost of electrical energy with 0.717% due to the fact that the kWh used per FU is insignificant. Additionally, welding equipment with a value of 0.018%.

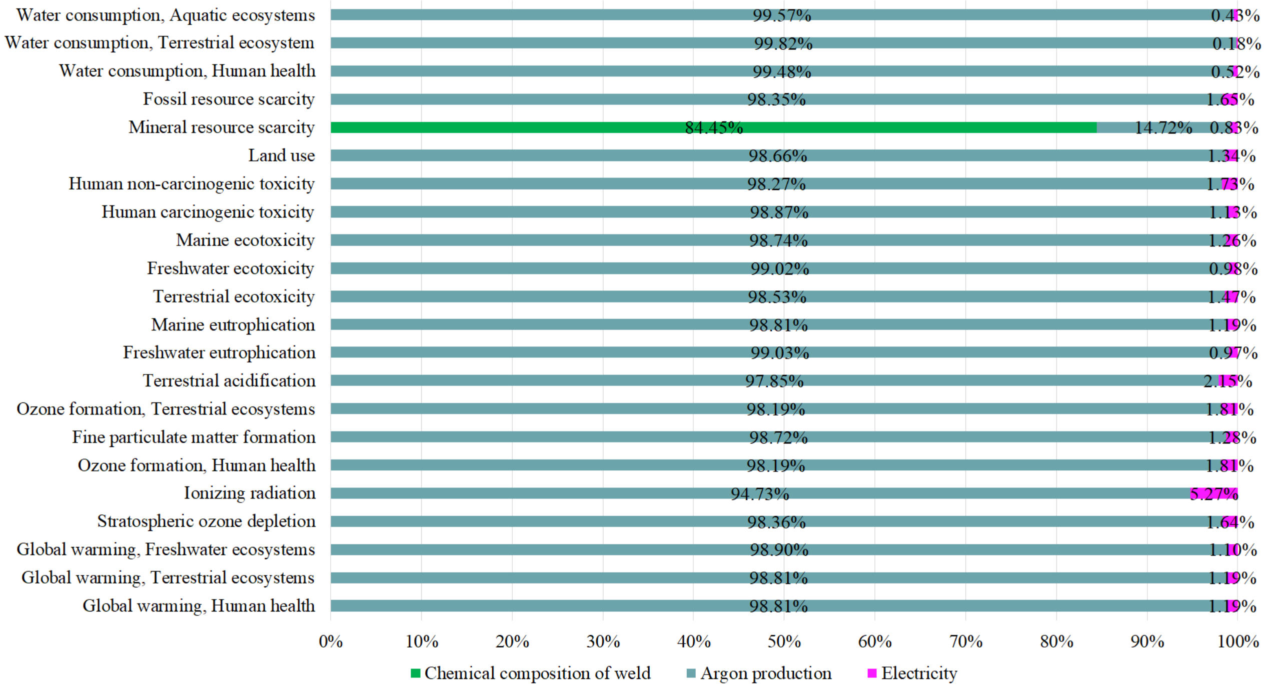


Figure 8. Environmental impacts of case study two, according to ReCiPe 2018 methodology.

However, it should be noted that the distribution of costs has been made on the basis of average process and tariffs in Spain, as explained in previous sections. However, the methodology used can be perfectly replicated elsewhere. With their respective prices and tariffs. Nevertheless, and, in general, independently of the percentages obtained from the costs. When welding operations are carried out, it is shown that the greatest weight and relevance is the cost of labour. This is followed by the cost of the consumption of shielding gas. Finally, the input materials and electrical energy.

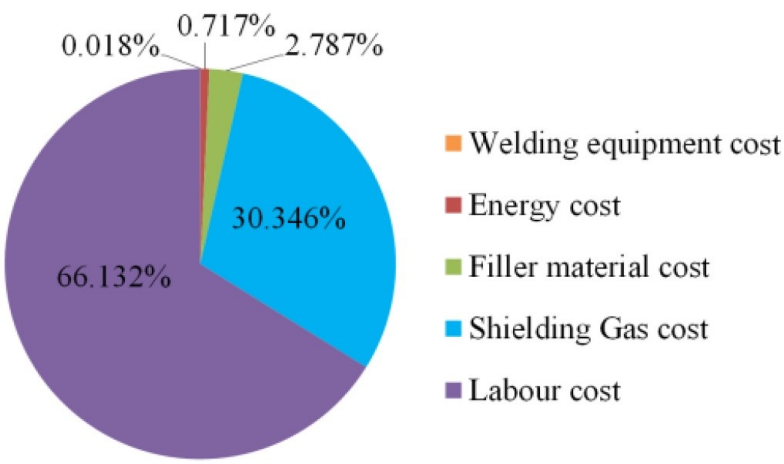


Figure 9. Average economic costs of case studies.

Figure 10 shows the distribution of all the costs analysed in the economic comparison according to each case study. Regarding the specific case studies, case study two (TIG welding with carbon steel filler) is shown to have the highest cost, at 1.96 € per FU. This is followed by case seven (TIG welding with stainless steel filler), with a cost of 1.48 € per FU, and, finally, case one (TIG welding on carbon steel without filler) at 1.14 € per FU. The higher cost of case study two is owing to the fact that the average welding time increased by 61.36%, which means that there is a higher labour cost.

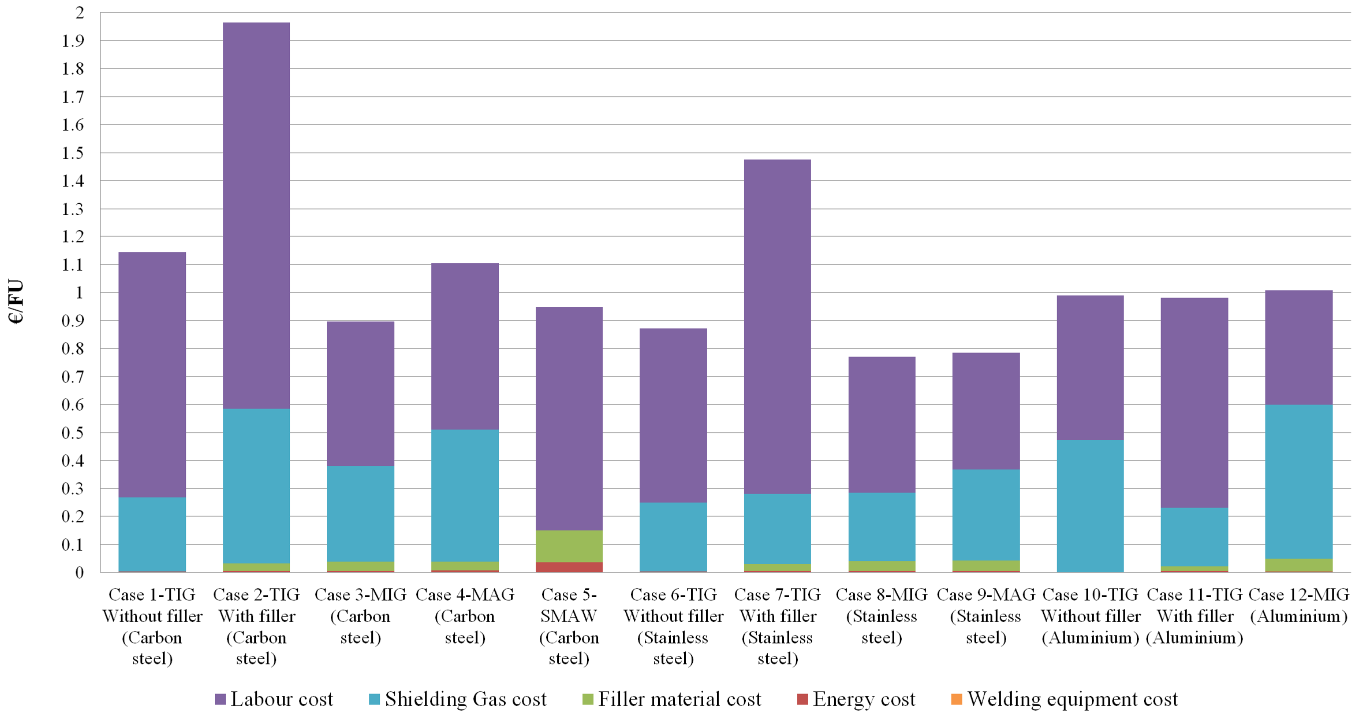


Figure 10. Economic distribution of costs for each case study.

The cost of the welding equipment is negligible, despite the considerable initial investment; extrapolating this expense per FU renders it imperceptible. Meanwhile, the consumption of electrical energy in all the case studies is minimal, with an average value of 0.064 kWh per FU. With the exception of case five (SMAW welding), this case study's electrical energy consumption is 384.4% greater than the average. This translates into 0.248 kWh more energy per FU produced. Therefore, of all the types of welding analysed herein, SMAW technology consumed the most electrical energy.

If we compare only the TIG welding technology without filler (cases one, six, and ten) and the MIG welding technology (cases three, eight, twelve), which were tested on carbon steel, stainless steel, and aluminium specimens, it can be observed that electrical energy costs were lower for aluminium test pieces than for those made with carbon steel, regardless of the welding technology utilised. In the case of TIG technology, the difference in electrical energy costs is 49.10% between carbon steel and aluminium specimens, whereas, in the case of MIG technology, the difference is 19.34%. However, for the shielding gas consumption variable, the opposite is true. Using aluminium test pieces increased consumption by 60.71% as compared to carbon steel specimens for MIG technology and by 78.88% for TIG technology. This indicates that using carbon steel specimens involves less shielding gas consumption but greater consumption of electrical energy to make the weld bead, and, therefore, more labour time. This finding means that functional units using carbon steel are more expensive than those using aluminium.

3.3. Combined Results

Lastly, this section addresses the combination of the most interesting results of this study. These are the economic cost per FU and the CO_2 emissions during the production process, as well as the impact on human health. Thus, a more comprehensive picture is provided of the most relevant factors in selecting one welding technology or another: the economic cost, CO_2 emissions from the production process, and how the welding process affects human health.

Figure 11 reveals that TIG technology has the highest economic cost per FU, with an average value of 1.48 €/FU and emissions per FU of 0.98 kg of CO_2. This is followed by SMAW technology with a cost of 0.947 €/FU and associated minimum emissions of 0.097 kg CO_2. In third place is MAG technology, with a cost of 0.944 €/FU and production of 0.385 kg of CO_2; and, finally, MIG technology with a total cost of 0.89 €/FU and emissions of 0.406 kg CO_2.

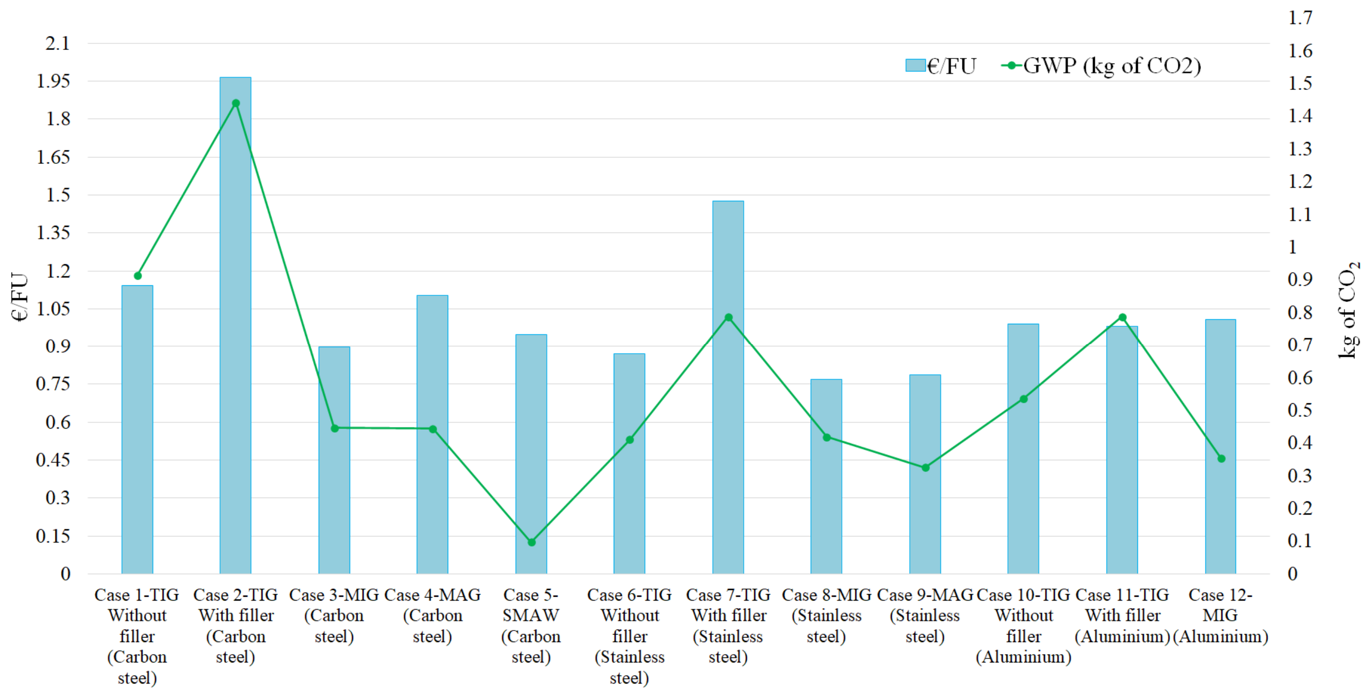


Figure 11. Economic cost per FU and its CO_2 emissions per case study.

It is noted that the use of TIG technology is the most expensive on average. Mainly due to the fact that the FU execution time with this technology is much longer. In comparison with other welding technologies. As on average for the case studies that have used this TIG technology, its execution time is 91.50 s per FU. This represents an increase with respect to the average execution time of other case studies of 24.77%. Additionally, directly derived from this execution time is an associated labour cost. This increases the total cost per FU. Another item that influences the TIG technology to be the most economically unfavourable is the use of shielding gas. In TIG technology, the use of shielding gas is higher compared to the other technologies. With an increase of 28.89%, which translates into consuming 4.77 L of shielding gas for each FU manufactured. Finally, the other variables, such as the cost of the input material, are not as influential. As can be seen in Figure 10, there are case studies with TIG technology without filler material (case one, case six, case ten) with a higher economic value compared to others (case three, case four, case five, case eight). Finally, the electricity consumption of the case studies using TIG technology is reduced by 38.71% with respect to the overall average of 0.0644 kWh. Taking into consideration these variables analysed for TIG technology, it is justified that it is the most economically unfavourable alternative. As a comment, if we talk about the materials, we can see that the use of carbon steel is more expensive than stainless steel and aluminium. As indicated above, welding carbon steel involves higher consumption of shielding gas and longer execution time.

A comparison of the existing technologies shows that the average difference between TIG technology, which is the most expensive, and MIG technology—the least expensive—is 39.94%. Therefore, a truly acceptable option is SMAW technology because, although its economic cost is high (36.21% less than TIG technology and 6.20% higher than MIG), it offers the best environmental results not only in terms of GWP (90.08% reduction) but also in other categories such as ozone layer depletion and abiotic depletion of fossil fuels. These drastic reductions in impact occur thanks to the absence of shielding gas in the welding process.

Figure 12 shows the results obtained for the final indicator of Human Health by applying the ReCiPe 2016 methodology to the case studies. It shows the unit values of impact on the category, expressed in DALY. Case two was found to have the highest impact on human health, followed by case one, case seven and case eleven. All of these cases used the same type of welding technology: TIG. This high impact is explained by the fact that these case studies consumed the largest amounts of shielding gas (argon). The most salient is case two with a percentage of affectation of 100%, which is equivalent to 3.51E-06 DALY. For cases one and seven, the reduction is 36.75% and 45.30%, respectively. On the other hand, for case five, which used SMAW welding, the effect on human health is 2.43×10^{-7} DALY, equivalent to 6.92%. Compared to case one, this represents a 93.08% reduction. This is because SMAW technology does not consume protective gases; therefore, the operator does not inhale these harmful gases during the welding process. The above results refer to the production of an FU. Hence, it is clearly necessary to protect the employee during these processes with the appropriate filtration equipment.

To conclude, it should be noted that the above graphs (Figures 11 and 12) for both the final human health indicator and the GWP impact category follow a similar trend despite their very different results and values. This common trend can be explained: the results have been extrapolated to a percentage value and compared with the rest of the categories/indicators. Thus, the percentage value is very similar for both, which means that a similar trend emerges when these results are represented graphically.

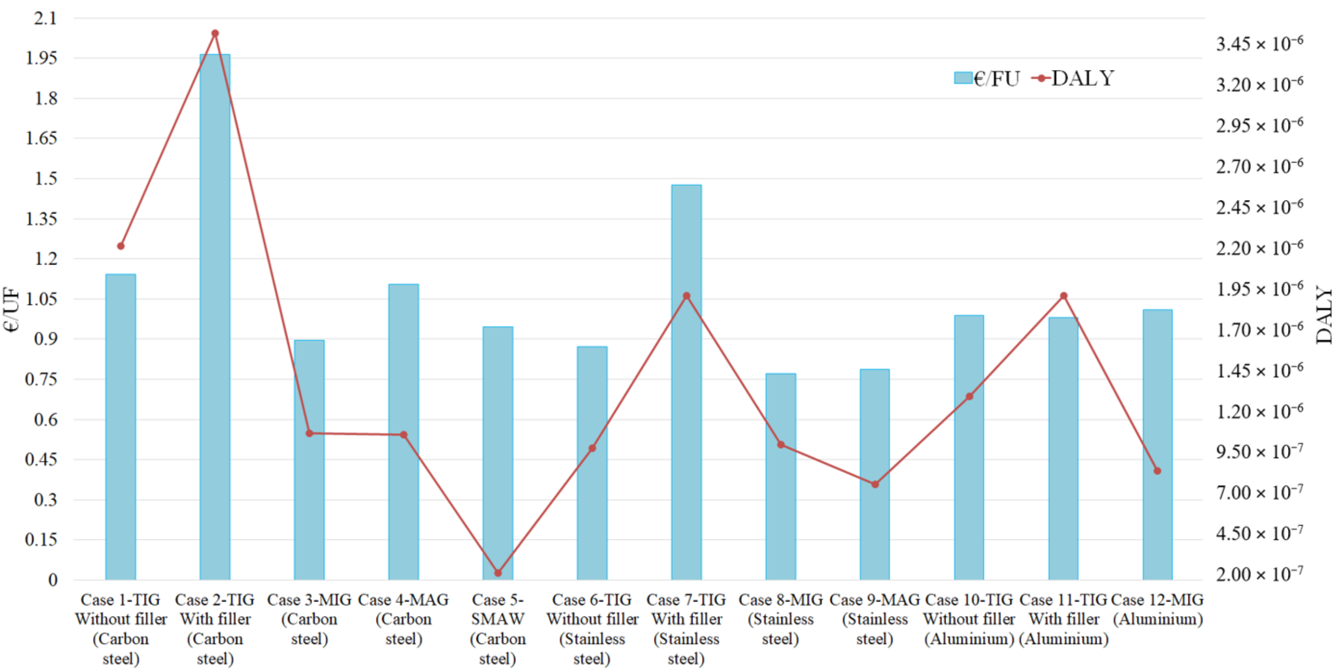


Figure 12. Economic cost per FU and its impact on Human Health.

4. Conclusions

The conclusions drawn by this study are:

The results obtained in the LCA show that the welds using the greatest amount of shielding gas had the greatest impact on the impact categories. As a result, TIG technology had a higher environmental impact than MIG, MAG, and SWAM technologies.

These differences are especially salient in impact categories such as GWP, wherein CO_2 emissions in case study two using TIG technology increased by 93.29% as compared to case study five using SMAW technology and by 77.42% for MAG technology in case nine.

The production of shielding gas is largely responsible for the environmental impacts produced by the case studies. This is highlighted by case two (TIG welding with filler). The LCA analysis of this case demonstrates that shielding gas production accounts for, on average, 94.07% of the impact in all the impact categories. Following shielding gas is the chemical composition of the weld bead with 30.62% of impact for the abiotic depletion elements category. Electricity consumption has an average impact of 2.11%.

During the welding process, harmful gases are released that affect human health. According to the final human health indicator, the greater the consumption of shielding gas the higher the impact on this indicator. This is highlighted by the behaviour of case two (TIG welding), with an effect of 3.51×10^{-6} DALY. Additionally, in other welding cases with less consumption of shielding gas, such as case nine (MAG welding), there is a 77.83% reduction, which translates into a score of 7.78×10^{-7}.

However, having demonstrated the danger of harmful gases to human health, it is nevertheless concluded that they can be controlled and removed. Therefore, their impact on the worker can be minimal. For instance, in welding workshops, the use of gas filter masks is compulsory. In this way, fumes from the welding process can be filtered out. Additionally, these can be prevented from being inhaled by the worker. In addition, the workshops have specific work areas for welding. These spaces are protected with extractors, which absorb gases that are harmful to health.

The foremost economic cost of the FU is labour. This is a direct consequence of welding execution time. Therefore, the case studies with the longest execution times, such as cases two, seven, and one, are those with the highest associated economic costs.

The costs derived from electrical energy during the welding process, although they varied across the different cases studied, have been proven to have a negligible economic impact. For example, in case study five (SMAW welding), which has the highest consumption of electrical energy, the energy cost has an impact of just 3.95% of the total FU.

The economic differences between the three metallic materials studied, when their use is compared for just one type of welding, are most notable in TIG welding. In the TIG process with filler, the material with the highest cost is carbon steel, as seen in case study one, which is 23.7% more expensive than the same process using stainless steel, as in case study six. Meanwhile, for the MIG process, the economic differences are less significant, for example, case study three using carbon steel is 16.4% more expensive than with stainless steel as in case study eight, and aluminium in case twelve falls between these two values.

Author Contributions: Conceptualization, C.G.-G., J.L.S.-O., E.F.-G. and J.F.-C.; methodology, C.G.-G. and J.L.S.-O.; software, J.L.S.-O.; validation, E.F.-G. and J.F.-C.; formal analysis, C.G.-G. and J.L.S.-O., E.F.-G. and J.F.-C.; investigation, C.G.-G., J.L.S.-O., E.F.-G. and J.F.-C.; resources, C.G.-G., E.F.-G. and J.F.-C.; data curation, C.G.-G., J.L.S.-O., E.F.-G. and J.F.-C.; writing—original draft preparation, C.G.-G. and J.L.S.-O.; writing—review and editing, J.L.S.-O., E.F.-G. and J.F.-C.; visualization, E.F.-G. and J.F.-C.; supervision, E.F.-G. and J.F.-C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by University of La Rioja, grant number REGI2023/21 and by Institute of Rioja Studies, grant number 2021 scientist.

Data Availability Statement: Not applicable.

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

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