Chapter

Design of a Sustainable Electric Pedal-Assisted Bike: A Life Cycle Assessment Application in Italy

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Abstract

Transport is one of the economic sectors within the European Union with the most detrimental effects on climate change. In this context, electric bicycles (e-bikes) are considered as a potentially effective technological innovation to reduce carbon impacts. The present research aims to propose a life cycle assessment study to quantify which components of a bicycle have the highest environmental impact. The use in Italy of two different bicycles, an electric pedal-assisted bike and a hydrogen-fuel cell-operated one, is analyzed. The final aim of the study is to quantify and to evaluate the bike's energetic and environmental performances, focusing the analysis on the vehicle production and use phases. To achieve the abovementioned purpose, two approaches, the "from cradle to grave" approach and "well to wheel" approach, are considered.

Keywords: sustainability, smart mobility, LCA, electric pedal-assisted bike, hydrogen-fuel cell bike

1. Introduction

Transport is one of the main causes of air pollution, climate change, and urban noise problem [1]. In fact, it is responsible for about one-third of the global consumption of energy and more than one-fifth of the damage caused by the greenhouse effect, global warming, CO_2 emissions, and human health [2]. In recent years, policies and incentive campaigns have been promoted for electric mobility in order to reduce the use of fossil resources and to limit the use of polluting motor vehicles.

The aim is to promote sustainable mobility, preserving the environment and improving the quality of life. Modern society is increasingly moving toward the use of zero-impact transport systems able to satisfy the needs of the user while achieving a reduction in consumption and harmful emissions [3]. The academic community and producers are paying close attention to a particular type of electric mobility that is represented by the *electric pedal-assisted bikes*. Electric pedal-assisted bikes have conquered the electric vehicle market, positioning themselves at the top of the classification, thanks to the technological innovation and to the cost reduction of electronic components [4]. Also known with the term *pedelec*, in the last decade, they have become one of the most used means of transport in the city thanks to the presence of the electric motor to support the pedaling [5].

The sector of electric bikes underwent strong development from 2006 to 2016 [6]. According to recent statistics, conducted in Italy, Germany, France, the United Kingdom, Holland, and Austria by Claus Fleischer, CEO of Bosch eBike Systems, it emerged that 10% of interviewed is already an e-bike owner, while 16% are considering buying one within the following year; preferences are oriented toward e-bike by city (29%), followed by trekking models (11%), urban (9%), and e-mountain bikes (8%), thus expecting an even more exponential growth for the next decade [7].

These ecological vehicles have their specific characteristics: (1) electric bicycles are not mopeds and (2) their speed is modest. This feature makes electric bikes usable by anyone, even without a license and without wearing a helmet.

These vehicles make it possible to combine the advantages of traditional bikes with those of mopeds, so much so as to be called the "ecological bicycles of the planet." The tendency is confirmed by the fact that the fight against pollution has pushed many cities of the world to rethink their mobility by favoring zero-impact vehicles.

The analysis of the state of the art of life cycle assessment (LCA) studies applied to the electric pedal-assisted bikes showed that studies on pedelec are still very few [8]. An interesting study was conducted by Blondel et al. [9] in November 2011 on behalf of the Financial European Commission, where a complete LCA analysis was carried out by the different types of transport (bicycle, pedelec, bus, car) in order to evaluate the CO_2 emissions from each of these vehicles during production, use, and disposal.

The aim of the present research was to evaluate the energy-environmental performance of an electric pedal-assisted bike, using the SimaPro© software. Specifically, the analyzed pedelec is the e-bike produced by an *Italian artisan company located in Milan (North Italy)*, active in the two-wheeler sector since 1908. The study followed the approaches "from cradle to grave" and "well to wheel."

The rest of the chapter is organized as follows: Section 2 presents a brief history of electric bikes; Section 3 analyzes the main rules and regulations governing electric bicycles; in Section 4 systems under study are presented; in Section 5 the methodological approach and the main assumptions of the study are explained; and, finally, Section 6 summarizes the main results and implications of the study.

2. A brief history of electric bikes

Normally, it is thought that e-bike is a relatively recent invention. The history of the ebike was made by brilliant and passionate inventors. The first bicycles with electric motors appear at the end of 19th century [10]. More precisely in 1895, Ogden Bolton Jr., an American inventor, decided to apply for the first time an electric motor on the rear hub of a traditional bicycle [11]. For many years, due to reduced autonomy, the production of electric bikes was difficult; electric bikes remained as simple prototypes. Only in the 1930s, more and more European companies began to produce complete models of e-bikes, even if the currently available technology did not yet give the possibility of producing light vehicles with great autonomy as happens today. One of the first successful models was made in 1937 by Philips, a famous and active company in the radio sector, in partnership with Gazelle, a company that produces traditional bikes of great renown in the Netherlands and in Europe (**Figure 1**). The model, which made 117 sales, had a weight of 50 kg net of the battery that was characterized by a range of 40 km. It needs to do a full day to charge the battery. The vehicle reached a speed of about 18 km/h.

Later in 1946, Benjamin Bowden, an Anglo-American industrialist very active in the automobile sector, launched the Spacelander, known as "The Bike of the Future" (**Figure 2**).

The bike, characterized by a modern design, was very interesting from a technical point of view, introducing ideas still valid today. Both the battery and the cables

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Figure 1.
The Philips-Gazelle 1937 electric bike (source: bikeitalia.it).

Figure 2.
The Spacelander (source: bikeitalia.it).

were integrated into the chassis, while the engine positioned in the rear hub also functioned as a dynamo to recharge the battery. Furthermore, according to the original patent, in a 10% climb, it could reach a speed of 8 km/h. However, the bike that represented a very high-end product, evidently too advanced for the time, was never produced on a large scale.

It is worth mentioning that from the second half of the twentieth century the low ecological conscience and cheap oil encouraged mass motorization reducing the interest in traditional and electric bikes. Only later, in the 1970s, the enormous rise in the price of crude oil and the spread of the first ecological movements renewed interest in electric vehicles [12]. The years following 1973 were of extreme importance for the technology behind electric bicycles. More and more designers began to patent e-bike models. In 1990, Michael Kutter developed what some people feel is the first Pedelec (PEDal-ELECtric). It later came to be referred to as Pedal Assist System (PAS). The first production models were sold in 1992 under the Dolphin name for the Swiss company Velocity, but they did not survive. In 1993 Yamaha developed its first electric bicycle, which included the now popular Pedal-Assist-System (PAS). Similarly, in the same period, other companies started their productions in Europe and Italy.

Subsequently, thanks to the use of sealed lead batteries and the experimentation of the lightest nickel-cadmium, electric bicycles were produced which are very similar to those of today, on a large scale and with affordable prices.

In the last 20 years, the electric bike models available to the public have multiplied dramatically, and several manufacturers have experimented with innovative technical solutions to achieve a better integration between pedaling and engine assistance. Today, the technological innovations have made the e-bike a vehicle to all effects capable of optimally replacing a car over medium-short distances.

3. Rules and regulations governing electric bicycles

To be considered as "lawful" bicycles and to be treated as traditional bicycles, electric bicycle models must possess the famous "Pas," i.e., the Pedal Assist Systems, facilitated by the electric motor [13]. There are two *macro categories* of electric bicycles: (1) *electric bicycles* (or e-bike) with acceleration system and (2) *electric pedal-assisted bicycles* (or pedelec).

The *electric bicycle* that owns the acceleration system is equipped with an electric motor driven by an accelerator lever, generally positioned on the handlebar that allows you to accelerate independently of the use of pedals. This type of ecological vehicle is not really an electric bike but is categorized as an "electric scooter," and as such, it is the object of matriculation, license plate, insurance, wearing a helmet, and all the operations to be carried out in the case of motor vehicles.

The *electric pedal-assisted bicycle*, on the other hand, is equipped with an intelligent electronic control unit that understands when the driver is using the pedals and when not activates the electric motor only if the pedals are in motion.

The European Directive 2002/24/EC specifies the characteristics of pedelecs and defines the pedal-assisted cycles as "bicycles equipped with an electric auxiliary motor having a maximum continuous nominal power of 0.25 kW, whose power is progressively reduced and subsequently interrupted when the vehicle reaches 25 km/h, or sooner if the cyclist stops pedaling" [14].

This definition is included in the Italian regulations or in Article 50/2009 of the Highway Code. The definition does not limit to this value the maximum speed of the bike but indicates that it can be overcome by relying only on the capabilities of the user, not being the pedelec equipped with an acceleration system.

The European Standard EN 14764 standard "City and trekking bicycles: Safety requirements and test methods," specifies safety and performance requirements for the design, assembly, and testing of bicycles and sub-assemblies intended for use on public roads, and lays down guide lines for instructions on the use and care of such bicycles.

In addition, the Directive 2002/24/EC of the European Parliament and of the Council of 18 March 2002 relating to the type-approval of two or three-wheel motor vehicles and repealing Council Directive 92/61/EEC establishes that all two or three-wheel motor vehicles must be equipped with the CE conformity marking consisting of the homonymous "CE" symbol.

In addition, each bicycle in accordance with the law must be accompanied by an instruction manual useful to the purchaser, containing the main information for the correct use of the vehicle and for its maintenance.

4. Systems description

The product analyzed in this study is not a generic pedelec is not a generic pedelec, but rather an electric pedal-assisted bike. Specifically, the prototype studied is the classic Corinto model produced by Italian artisan company located in Milan (Northern Italy), to which the bike + all-in-one system of Zehus human+ has been incorporated, as shown in **Figure 3**.

The prototype has the following features:

- Aluminum frame
- Bike + all-in-one propulsion system from Zehus human + with:

Figure 3.
The pedelec prototype.

- ○ Brushless motor, with rated power of 250 W and nominal voltage of 24 V, complete with engine control unit (ECU)
- ○ Lithium battery with battery management system (BMS) associated with the capacity of 160 Wh
- ○ A control unit (pedaling sensor—PAS, two speed microcontrollers, integrated Bluetooth module for controlling the vehicle)

- Rear and front rod brakes
- 28-inch rubber wheels
- Saddle and handlebar from the Miele B66 series, made by Brooks

The battery, recharged by a simple power outlet, powers the engine, which is started as soon as the pedal sensor detects the movement of the pedals. The whole system, thanks to the presence of the control unit and the Bluetooth unit, is controlled using a telephone app for Android and iOS systems.

The characteristics of the H-bike considered as well as the data refer to the articles of Kheirandish et al. [15], Cardinali et al. [16] and Mellino et al. [17] and are summarized in the following. The H-bike has a 250 W PEM fuel cell system, an electronic control unit (ECU), a rechargeable nickel-metal hydride (Ni-MH) battery of 25 V and 9 Ah, 2 converters 150W DC/DC, a 150 W electric motor and a hydrogen storage tank. The PEM cell, consisting of 3 main parts: cathode, anode and proton exchange polymer membrane (Nafion), transforms the chemical energy, released during the electrochemical reaction between hydrogen and oxygen, into electrical energy.

5. Materials and methods

5.1 Goal and scope definition

The aim of the study was to evaluate the energy-environmental performance of a pedal-assisted bicycle prototype, according to the ISO 14040 series standards and the International Reference Life Cycle Data System (ILCD) [18, 19].

The study, conducted according to the life cycle assessment (LCA), is focused on the analysis of the *production* and *use* phases of the vehicle. Specifically, the phases of the life cycle were examined, involving the extraction of raw materials up to the finished product and from the finished product to use. A comparative analysis was carried out between the pedelec prototype and the H-bike, an equally innovative technology. The analysis was carried out considering two main approaches one for each phase:

Phase #1: "From cradle to grave" approach. An assessment was carried out of the environmental impacts of the production of vehicles and of the elementary components starting from the extraction, production, and use, up to the recycling and disposal of the residual waste.

- *Phase #2: "Well to wheel" approach*. The environmental impacts and energy vectors used during pedelec prototype operation have been estimated. Materials and the energy used have been evaluated according to a "well to wheel" approach, i.e., considering the phases of production of energy carriers (electricity and hydrogen).

In the first case, a bicycle unit was chosen as the functional unit, to which all materials, emissions, and energy consumption were referred.

Instead, in the second case, it was used as a functional unit 100 km.

Really, transport studies use a functional unit expressed in passengers for kilometers traveled p-km. However, in our study, being the pedelec prototype used by a single person it was considered appropriate to refer to the distance only. Nevertheless, in the **Figure 4** the scheme used for the assessment of the usage phase is given.

5.2 Main assumptions

Once the functional units have been defined, some assumptions have been made to conduct the study, as defined below:

Hypothesis 1: The same bicycle structure (for both bikes) was considered in terms of size, composition, and materials to concentrate the study on electrical technologies and evaluate the real environmental impacts of the two different systems.

Hypothesis 2: For the pedelec prototype, which has a lithium battery of 30 V and 5.3 Ah, 1000 recharging cycles have been considered, for which an efficiency of the processes of charge and discharge constant throughout the life span has been

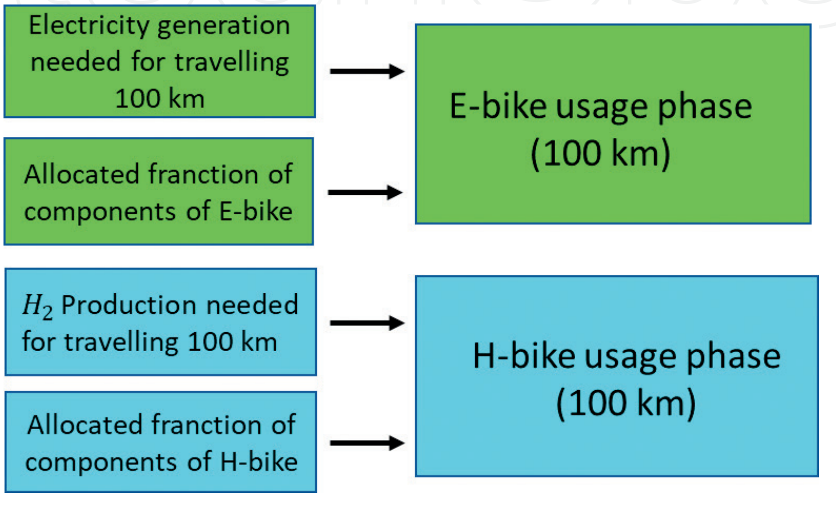

Figure 4.
LCA scheme used for assessing the usage phase.

assumed. Moreover, during use, the speed of the vehicle was set at 25 km/h. It was considered that compared to a full charge the autonomy is 35 km with activation of the kinetic energy recovery system (KERS) system and 25 km in case of absence energy recovery braking.

Hypothesis 3: According to *Hipotesis 2*, a life span of 35,000 km was considered in the first case and 25,000 km in the second.

Hypothesis 4: For H-bike, on the other hand, a duration of the PEM fuel cell equal to 120,000 km was hypothesized, as suggested by the US Department of Energy (https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/accomplishments.pdf).

Hypothesis 5: Subsequently, according to hypothesis 1, for both cases, a life span of the bicycle and the other system components of 120,000 km was assumed.

Hypothesis 6: Furthermore, it was assumed that the hydrogen, used during the use phase, was produced by electrolysis from a photovoltaic refueling station; while for recharging the lithium battery, electricity taken directly from the network was used first, then from the typical Italian energy mix, and then subsequently, the electricity withdrawn from the grid, produced through a renewable electric mix. For this purpose, the mix proposed by the Enel Green Power society was used (https://www.enelgreenpower.com).

5.3 Inventory analysis

In the inventory analysis phase, the input and output flows of material and energy were identified and quantified, and the emissions into the air, water, and soil involved in the production phase of the e-bike. The data were provided in part by the company (see **Tables 1** and **2**) and partly retrieved from the literature and from the databases contained in SimaPro©. Ecoinvent database was used since it is one of the most complete and the most used for European LCAs [20].

In particular, for the structural part of the bike, a process already existing in SimaPro© was used with the name "bicycle," which was appropriately modified according to the information obtained and the values identified in order to adapt it to the prototype.

For the propulsion system, it was considered an electric motor of a scooter, which for size was close to that of Zehus. While, the control unit has been schematized with a generic process called "electronics, for control unit", having no detailed information on the sensors and the materials used.

Instead, for the lithium battery, we used the "battery cell, Li-on" process that reproduces it faithfully, modifying the data on the battery capacity and inserting the weight of the battery. **Figure 5** shows the process tree for production phase of pedelec prototype.

Components	Materials	Length	Outer diameter	Internal diameter
Horizontal pipe	Aluminum	595 mm	36 mm	32 mm
Vertical tube	Aluminum	470 mm	36 mm	32 mm
Oblique tube	Aluminum	520 mm	36 mm	32 mm
Horizontal sheath	Aluminum	420 mm	25 mm	—
Vertical sheath	Aluminum	435 mm	25 mm	—
Steering tube	Aluminum	140 mm	36 mm	32 mm
Fork	Aluminum	524 mm	30 mm	—

Table 1.
Pedelec prototype frame data (source: Italian artisan company located in Milan (North Italy)).

Components	Technical features	Weight
Engine	250 W–24 V	1.7 kg
Battery	160 Wh–5.3 Ah	600 g
Control unit	Four sensors	200 g
Coating	Aluminum	500 g

Table 2.
Bike + all-in-one propulsion system data (source: Zehus).

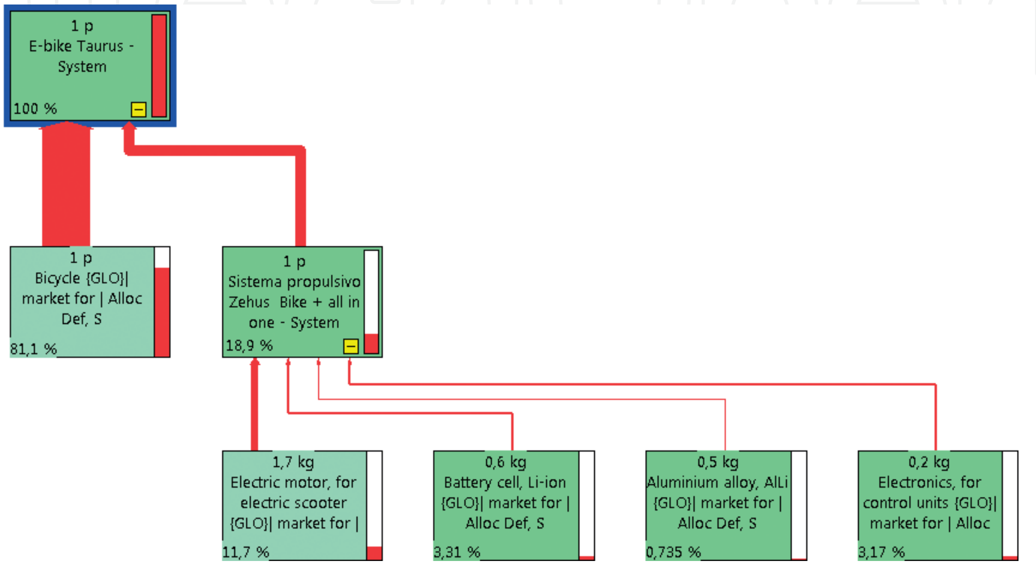

Figure 5.
Process tree for production phase of pedelec prototype (SimaPro©).

Instead, with reference to the H-bike, used as a comparison system, the data necessary for the reconstruction of the model were taken from the study conducted by Mellino et al. [17]. Specifically, for the bike structure, the same e-bike process was used, to analyze the two models with the same chassis, while for the innovative technology, all the processes necessary for the reproduction of the PEM cell were recreated. In the hydrogen bike model, have been added the following processes:

1. The "bicycle" and "PEM stack cell" processes to the hydrogen accumulation;

2. The process for the nickel-metal hydride storage battery

3. The processes "electric motor, for electric schooter" and "convert, for electric passenger car" to recreate the engine and the DC/AC converter. The process tree is shown in **Figure 6**.

Instead, for the use phase of the e-bike, not yet this commercialized, reference was made to data in the literature and in the Zehus manual. In fact, 1000 cycles of recharging have been considered for the lithium battery, and the speed of the bike has been set at 25 km/h. Thus, the manual has been identified as the autonomy of the bike in terms of km traveled equal to 35 km with activation of the KERS and 25 km in the absence of energy recovery during braking. Depending on the cycles and speed, and therefore of the kilometers traveled, the battery wear was defined not in terms of cycles but in terms of km having to relate to the functional unit (100 km). In fact, it was equal to 35,000 km in the first case and 25,000 km in the

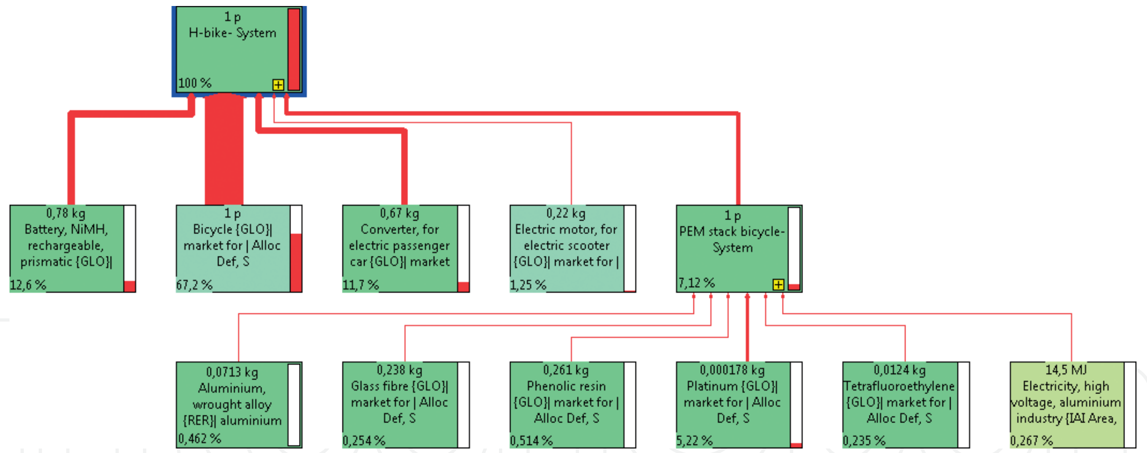

Figure 6.
Process tree for production phase of H-bike (SimaPro©).

second. Based on this information, a complete recharge of 160 Wh is required; the use phase reconstructed in the following figures has been reconstructed.

For the use phase of the H-bike, the data were retrieved only from the literature. A study conducted by the Department of Energy of the University of the United States has identified the data on the wear of the PEM cell equal to 120,000 km. The study conducted by Mellino et al. [17] has found the amount of hydrogen equal at 75 g, to complete 100 km. For which the information is known similarly before the tree has been recreated for the use phase of the H-bike.

Similarly, process trees for use phase were performed with SimaPro©.

5.4 Results from the Impact Assessment

The energy-environmental performance of the prototype was assessed in the production and use phases of the vehicle, using the IMPACT 2002+ method [21].

5.4.1 Classification

Impact categories have been chosen according to the Impact 2002+ method to have a global vision of the impacts of the pedelec in the production and use phases. In all, 14 impact categories were analyzed. The considered midpoints are shown together with the respective reference substances in **Table 3**.

5.4.2 Characterization

Using characterization factors typical of the IMPACT method, the scores of the different elements according to the kilogram equivalents of the reference substance of each category were quantified for each impact category. **Figure 7** shows the environmental impacts of pedelec and H-Bike for each impact category for production phase.

Similarly, we calculated the impacts for the use phase.

Figure 8 shows the results obtained from the comparison of the e-bike, in the case with and without KERS activation, with the hydrogen bike.

For the use phase, the process was also recreated assuming that the energy used to recharge the battery is produced from renewable sources through the "Green Mix of Enel" project. **Figure 9** shows environmental impacts of pedelec, with and without KERS, and H-Bike for each impact category for use phase and in the case of Enel Green Power.

Midpoint	Units
Carcinogens	kg C2H3Cl eq
Non-carcinogens	kg C2H3Cl eq
Respiratory inorganics	kg PM2.5 eq
Ionizing radiation	Bq C-14 eq
Ozone layer depletion	kg CFC-11 eq
Respiratory organics	kg C2H4 eq
Aquatic ecotoxicity	kg TEG water
Terrestrial ecotoxicity	kg TEG soil
Terrestrial acid/nutri	kg SO2 eq
Land occupation	m2org.arable
Aquatic acidification	kg SO2 eq
Aquatic eutrophication	kg PO4 P-lim
Global warming	kg CO2 eq
Nonrenewable energy	MJ primary
Mineral extraction	MJ surplus

Table 3.
Impact and damage categories; IMPACT 2002+ method.

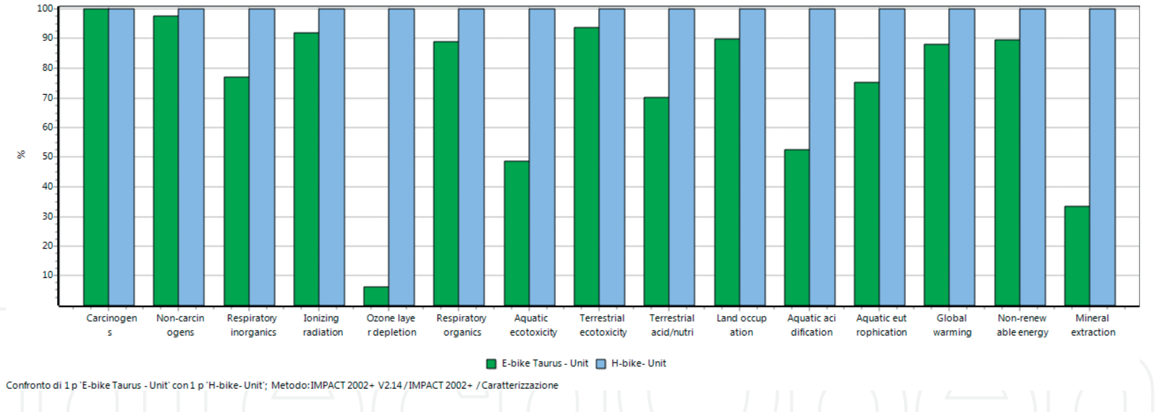

Figure 7.
Environmental impacts of pedelec and H-Bike for each impact category for production phase.

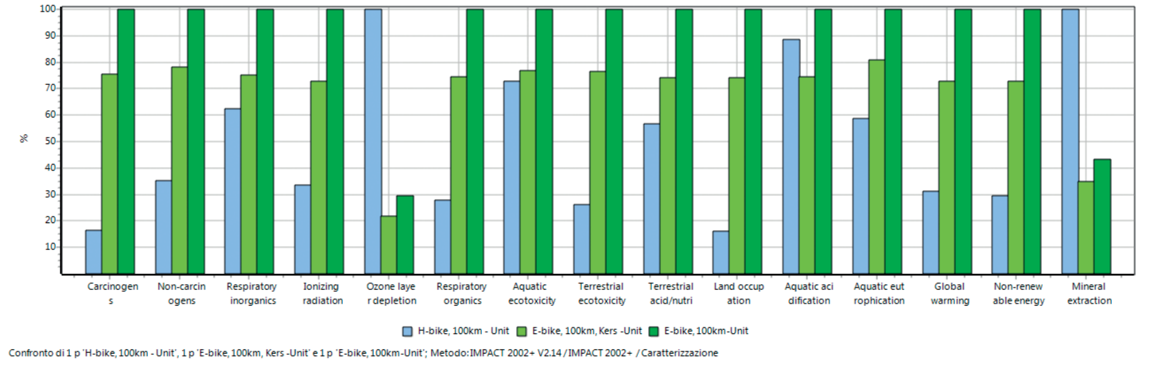

Figure 8.
Environmental impacts of e-bike, with and without KERS, and H-Bike for each impact category for use phase.

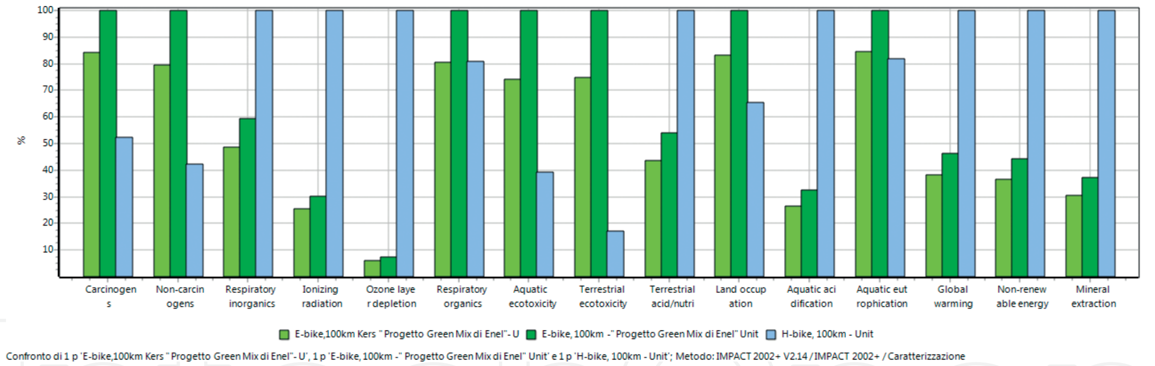

Figure 9.
Environmental impacts of e-bike, with and without KERS, and H-Bike for each impact category for use phase (Enel Green Power).

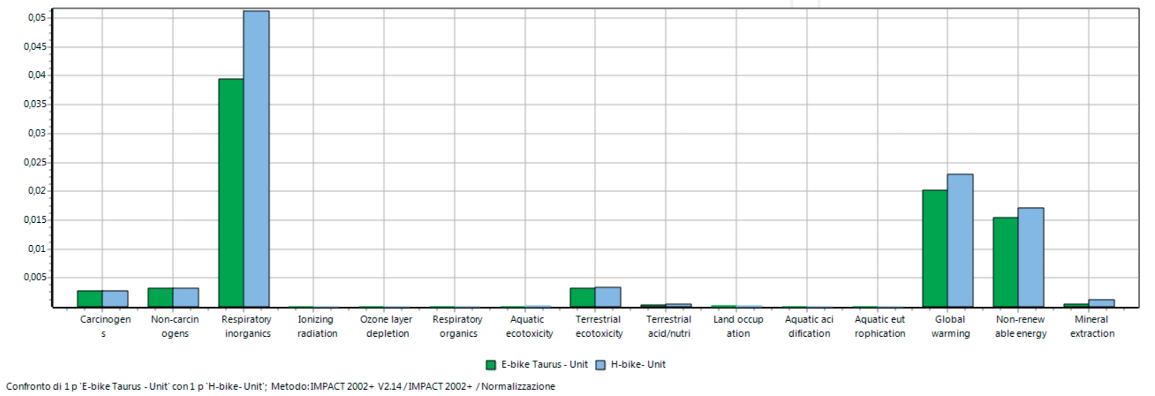

Figure 10.
Comparison of the impact categories between e-bike and H-bike for production phase.

5.4.3 Normalization

This phase aims to determine the importance of the individual environmental effects, dividing the impacts of each category by the respective reference values, represented by average data in a world, regional, or European scale, referring to a given time interval, generally 1 year.

Figure 10 shows comparison of the impact categories between pedelec and H-bike, for production phase.

The results show that of the 14 impact categories the ones that most weigh on the final pollution are essentially the following three:

- Respiratory inorganics
- Global warming
- Nonrenewable energy

Similarly, the procedure was subsequently applied to the use phase.

A greater impact of the categories has been confirmed: respiratory inorganics, global warming, and nonrenewable energy.

5.4.4 Damage assessment

In this phase, the impacts, identified in the characterization, were grouped into four categories of damage, human health, ecosystem quality, climate change, and resources, according to the logic shown in **Table 4**.

Impact categories	Damage factors	Damage categories	Unit of measurement
Carcinogens	2,80 E-6	Human health	DALY
Non-carcinogens			
Respiratory inorganics	7,00 E-4		
Ionizing radiation	2,10 E-10		
Ozone layer depletion	1,05 E-3		
Respiratory organics	2,13 E-6		
Aquatic ecotoxicity	5,02 E-5	Ecosystem quality	PDF*m2*yr
Terrestrial ecotoxicity	7,91 E-3		
Terrestrial acid/nutri	1,04		
Land occupation	1		
Aquatic acidification	8,86 E-5		
Aquatic eutrophication	8,86 E-5		
Global warming	1	Climate change	$kg\ di\ CO_2$
Non-renewable energy	1	Resources	MJ
Mineral extraction	1		

Table 4.
Damage categories.

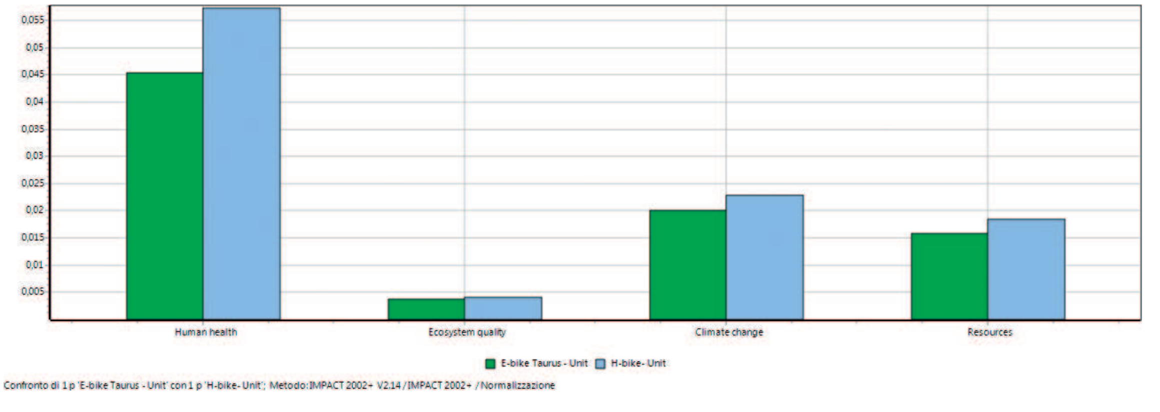

Figure 11.
Comparison of the damage categories of pedelec with H-bike for production phase (normalized).

Figure 11 shows the four endpoints identified for the production of the pedelec. The values identified were then normalized.

Similarly, the damage categories for the use phase of the pedelec, with and without KERS (with and without normalization), were identified.

The comparison of the impact categories of the pedelec has also been calculated with and without activation of the braking energy recovery system with those of the H bike, again in the use phase.

5.5 Discussion

5.5.1 Comparative analysis of the production phase

The results show that the processing of the e-bike is less impactful in all the categories considered than that of the H-bike.

This result is due to a greater complexity of the H-bike, which requires the use of special materials and complex processes for the control unit and the PEM fuel cell along the production chain.

Both processes mainly impact on the respiratory inorganics category, even if there are not negligible effects on the categories of global warming and nonrenewable energy, while in the others, there are minor impacts, almost negligible.

As far as respiratory inorganics is concerned, the pedelec generates a 1.2 times lower impact than the H-bike (respectively, 0.4 and 0.519 kg PM 2.5 eq), thanks to the presence of a structurally simpler propulsion system than to what characterizes the hydrogen bike.

Specifically, analyzing the different contributions of the processes related to the construction of the pedelec, it is clear that the greatest impacts are generated by the structure of the bike, due to the processing of large quantities of aluminum.

As the objective of the present research was to assess the sustainability of electrical technology, the impact categories for the bike + all-in-one propulsion system were analyzed. It emerges that the major impacts are caused by the electric motor of the Zehus system, which accounts for 61.31%, followed by the control electronics and the lithium battery, with the respective percentages of 17.46 and 17.38%.

Regarding the impact of the electric motor, the cause is closely linked to the use of copper for the construction of the rotor, as well as the use of high- and medium-voltage energy, produced from nonrenewable source, used during the process of engine production.

For the control unit, the impact is associated with the main body of the control unit, i.e., the board, which requires rather complex operations for the realization of the components that constitute it, as well as the use of not negligible energy, for which it has been supposedly a world energy mix, considering that most of the electric elements are not manufactured in Italy, but rather imported.

For the lithium battery, the greatest impact is related to the production processes carried out for the construction of anode and cathode.

For the global warming impact category, it is still the engine that generates the greatest impact with 60%, even if this time the cause is no longer made of copper but rather the harmful substances emitted during the processing of permanent magnets used in the brushless motor and to an equal extent by the production processes of aluminum and by the use of medium-voltage energy always produced from fossil fuels, followed by the control electronics and lithium battery whose cause is always represented by aluminum.

Despite this, the electric bike is still better than the H-bike, whose high impacts are linked to the nickel metal hydride accumulation battery, to the processing of platinum used in the construction of the cell and to the complex control unit. In fact, unlike the one installed on the e-bike, it is responsible for supervising the system parameters such as stack temperature, hydrogen pressure, cell voltage and current, battery voltage, and start-up and shutdown of the system, to control the environmental conditions that influence the behavior of PEM.

5.5.2 Comparative analysis of the use phase

The results show that unlike what is seen for production, it is the H-bike that impacts less in all the midpoints considered, except for ozone layer depletion and mineral extraction.

The pedelec bike with or without KERS causes respiratory categories inorganics, global warming, and nonrenewable energy the greater pollution than the hydrogen bike.

More specifically, in the case of activation of the energy recovery system, it generates a lower impact than the bike without KERS but 3.2 times higher than the H-bike in the respiratory inorganics, 2.34 times in global warming, and 2.46 times in nonrenewable energy.

In the absence of the braking energy recovery system, the impacts are even higher.

Renewable source	Quantity
Hydroelectric	49.90%
Geothermal	23.80%
Wind	23.70%
Solar	2.60%

Table 5.
Enel Green Mix project data (source: Enel Green Power).

The pollution, for all three midpoints, is closely linked to two causes:

1. The battery recharge process, and

2. The use of the Italian electric mix produced for the most part (a nonrenewable source).

In fact, in the case of H-bike, the energy used to produce hydrogen is generated by solar radiation.

Since energy is the main cause of pollution, the use phase has been repeated assuming the use of renewable energy, in order to evaluate the dependence on the performance of the e-bike from the Italian electric mix. In fact, a green and renewable production scenario was built, starting from the data of the "Green Mix" project by Enel Green Power reported in **Table 5**.

The impacts of the pedelec have been reduced compared to the phase previously shown. In addition, in the categories where it first had the most impact on the pedelec, the impacts decreased compared to the H-bike. This demonstrated the sustainability of the vehicle and the strong dependence of the pedelec performance of the electric mix used.

6. Conclusions

In the present research, the life cycle assessment methodology was used to evaluate the energy-environmental assessment of the pedelec prototype during the production and use phases of the vehicle. The results identified were compared with the results obtained in H-bike. The main consideration of the study can be summarized as follows:

- In the production phase (developed according to the "from cradle to grave" approach) emerged that the construction of the H-bike has more impact than the pedelec prototype in all the midpoints considered due to the presence of a rather complex control unit.

- The most affected category was respiratory inorganics, followed by global warming and nonrenewable energy. The causes are closely linked to the processing of aluminum and copper, to the harmful substances emitted and to the consumption of energy from the Italian and global electric mix, for the construction of the bike structure and the electric propulsion system.

- The environmental performance of the pedelec deteriorates compared to those of the H-bike when the boundary is moved to the operational phases of the vehicles, due to the use of the Italian electric mix for the battery charging process.

- The environmental performance of the pedelec bike in the use phase improves compared to those of the H-bike when the energy used to recharge the lithium battery is produced from renewable sources.

- The energy mix used for the production phase and for the transport phase influences the performance of the vehicles, generating not negligible environmental impacts.

Considering these results, future efforts are still needed to further reduce the impacts of the pedelec; improvements can be made on the materials used to build the pedelec structure and the propulsion system.

The aluminum, copper, and steel components could be replaced with recycled or more innovative materials. However, electrical technology is still a valid and clean solution for the world of transport, even if now the costs remain quite high.

In addition, future research aims to investigate the disposal and recycling phases.

Conflict of interest

The authors certify that they have no conflict of interest.

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