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Sustainability in electric drive productionCreation a Life Cycle Assessment (LCA) for electric drive production.

Trabajo Fin de Máster

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II List of Symbols and Abbreviations

Abbreviation	Description
EDT	Electric Drive Technology
E-Drive	Electric Drive
EVs	Electric Vehicles
LCA	Life Cycle assessment
BEV	Battery Electric Vehicle
HEV	Hybrid Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
V2G	Vehicle-to-grid
DC	Direct Current
AC	Alternating Current
IM	Induction Motors
PM	Permanent Magnet
OEMs	Original Equipment Manufacturers
ICEV	Internal Combustion Engine Vehicle
SDM	Sensing Diagnostic Module Motor
SRM	Switched Reluctance Motors
ASM	Asynchronous Motors
ICE	Internal Combustion Engine
LCI	Life Cycle Inventory
GE	Germany
LCIA	Life Cycle Impact Assessment
APOs	Accumulative Pseudo Static
CAPOs	Consequential Accumulative
ReCiPe	Resource and Environmental Profile
EDIP	Environmental Damage Impact Potential
H, A	Harm to Air

I, A	Harm to Ingestion of Air
E, A	Harm to Ecosystems and Human Health
BMW	Bavarian Motor Works

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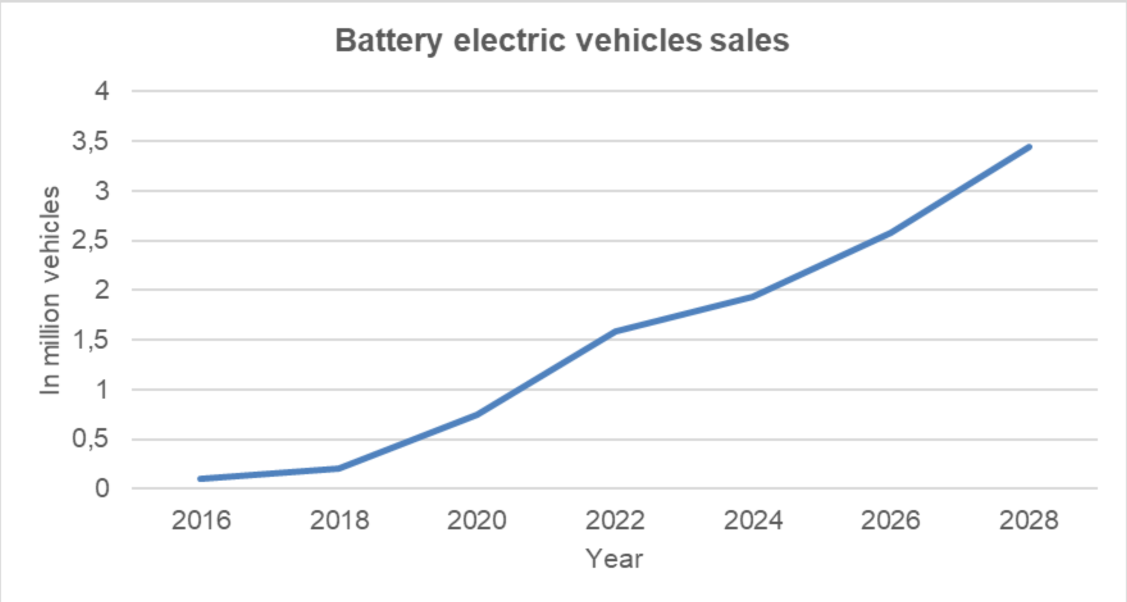
1 Introduction

During the last decade, the adoption of electric drive technology (EDT) has become increasingly important in promoting sustainability in the current world, as it reduces the reliance on fossil fuels and reduces harmful emissions that contribute to air pollution and climate change. The electric vehicle together with other solutions as hybrid vehicles, solar-powered vehicles or hydrogen-fuelled vehicles are taking an important role in the transition from the more common combustion engine vehicles.

As it can see in the figure behind, the electric vehicles sales in Europe have been increasing in the last years. Therefore, is it clear that people have become more aware about the important of the carrying about the environment and the effects of their life in it. Also recently, Tesla model Y is now in the fourth position of the selling in Germany, only behind of other combustion engine cars as Volkswagen Golf or T-roc. Globally, in 2020, the electric car stock was hitting the 10 million marks[1], what was a 43 % increase over the year before.



Graphic 1: BEVs sales in Europe[1]

Although the alternatives are increasing the efficiency and the drive performing, there are still some disadvantages about the use of electric cars, as for example the cost and charging station availability. In this context takes importance another aspect, the sustainability. This has become a buzzword in the industry, alongside like industry 4.0 and artificial intelligence. All these concepts share the goal of increasing efficiency and effectiveness, while minimizing environment impact.

[1] Cf. Statista Market Insights. 2023.

As it is known, the battery is currently the most important part for the companies and therefore in the focus of the politics and laws. Besides, the electric drive train is also a critical component of an electric vehicle, and its manufacturing involves rare earth materials that can harm the environment and human lives. Therefore, there needs to be more emphasis on the sustainable aspects of electric motors and their production. Is for this that in a current studio in the Capgemini Research Institute, it was found that 62% of automotive organizations have a comprehensive sustainability strategy to produce electric motor components with defined goals and targets.[2]

To sum up, one of the priorities of the companies right now is to achieve the production of the electric vehicles' components more sustainable. It's because of that, for what makes sense to focus- in this master thesis on the production stage of the components and how they can be made in a more sustainable way to achieve the overall goal.

1.1 Motivation

The benefits of e-drive technology for sustainability are numerous. For example, electric vehicles (EVs) emit zero emissions, which helps to reduces air pollution in urban and natural areas. Additionally, EVs are more efficient than traditional combustion motor vehicles, which reduces the amount of energy needed to operate them and can help to lower greenhouse gas emissions. Furthermore, e-drive technology can be paired with renewable energy sources such as solar or wind power, which further reduces carbon emissions and promotes sustainability.

However, the use of e-drive technology is not limited to passenger vehicles alone. Many other forms of transportation and machinery, such as buses, trucks, trains, ships, and construction equipment, can also be electrified. By transitioning to electric power these industries, it would be possible to reduce emissions and promote sustainability in many sectors of the economy.

Overall, the adoption of e-drive technology is an important step towards achieving a more sustainable future. So, now that electric vehicles are on their way to be the first technology used in the vehicles industry, research on electric motors becomes much more critical than before.

However, as battery technology continues to improve with all the effort of the companies, these ones are now also focused in the search of a method that helps to produces the e-drive train elements of the electric vehicles in a more sustainable way, as for example, the new lightweight, compact and high-efficiency powertrain for EVs from Nissan Motor Corporation, or BMW's Fifth-Generation Electric Motor which is

[2] Cf. Capgemini (Report-The-Automotive-Industry-in-the-Era-of-Sustainability) 2020.

knowing like a Magnetic free masterpiece. They are using modern materials and its high-tech sealing technology to avoid the generation of dust in the brushes and commutators of the rotor, which is the main reason for the replace of an electric motor.

Because all of this new tendencies, there has been a lot of potential seen in the design and functioning of electric motors and this mater thesis is trying to put the point of view in the searching for the best way to produce these elements and trying to analyse the LCA of an example of stator production to find a common overview of where the main task is to improve and to find new solutions in this area.

This motivates me to take up this as my thesis topic to get deep into the topic of electric motors, their current development, and research on how they can be produced more sustainably.

1.2 Research Question and Methodical approach

The thesis work will essentially try to quantify the impact of the electric power train on the sustainability of electric vehicles, with the creation of a Life Cycle Assessment using as data source, the HaPiPro[2] project.[3] This is focusing on the variant-flexible production of hairpin stators, with numerous renowned industrial partners. In this context, a prototypical demonstration line is used on the premises of the Ford plants in Cologne, and here different variants of the e-motor have been produced to achieve a better performance and efficiency. At the end, this thesis will answer main research questions such as: How much impact in the environment does the production of the electric power train in the electric drive sector using the hairpin stator as an example? These results can be taken to another type of electric train production and give conclusions about it? There are better ways of production of it that could help to reduce the impact and which? Which are the processes or flows in this production that have the most critical values in this aspect, how could they be improved?

The methodical approach will consist in first place of a systematic literature review on electric drive technology in general and the current situation of the sustainability in the industry, with an overview of different dimensions like economical, ecological. It will include research on the overall production process and of different stator and rotor (on electric motors) from a sustainability point of view.

Once the sustainability general outline is shown, the use of the LCA methodology will be studied in the e-drive sector, with which the main topic of this master's thesis will be introduced, the realization of an LCA. To realise this task, it will be supporting on the different databases achieved, that have been shared by the creators of the project, and

[3] Cf RWTH (Chair of Production Engineering of E-Mobility Components (PEM)) 2020.

analysing them, with the help of different software such as Eco-Invent or OpenLCA, which will help to calculate and identify main drivers through the LCA, by process, flow, or impact category.

Before the implementation of the model in the different tools, the target space needs to be defined with the support of the HaPiPro[2] project Database. Firstly, the production of the hairpin stator is shown, and the different steps defined, with the objective of having a good knowledge in the more important phases to study. Secondly, the different types of methodological LCA are developed and the choice of the method to be followed is shown and justified. After it, the LCA will be developed and will aim to identify areas of improvement and guide decision making towards more sustainable practices in the production of the electric drive production.

In the end, I will be able to analyse the results, and these will be assessed critically to work out the currently existing challenges in the sustainable production of Hairpin stators. Additionally, the created results, will be transferred to other cases, as for example the rotor production or the complete electric motor assembly, to create a holistic overview.

Finally, the literature on electric drive and his components as well as in the sustainability in the sector, and the analysis report of the LCA developed, will be combined to draw conclusions about the production of the electric motors and their components, and ask the research questions projected. Also, as a conclusion, some improvements to be made on the future will be shown.

2 State of the art: E-drive technology and sustainability

In this section, the state of art in the e-drive technology area is inspected as well as the sustainability analysis in this topic.

As the world transitions towards a more sustainable future, the production of electric drives has emerged as a key area for investigation. Electric drives, including electric motors, batteries, and power electronics, are integral components of electric vehicles and renewable energy systems. After many years of development, Electric Vehicles (EVs) technologies are becoming better, and advances technologies are employed to extend the driving range and reduce the cost of them.

In general, EVs are classified into three major categories according to the way and the place of production of electricity:[4]

1) **Battery Electric Vehicles (BEV):** Fully powered by electricity and the most efficient one.
2) **Hybrid Electric Vehicles**
   a) **Hybrid Electric Vehicle (HEV):** The vehicle uses both, the internal combustion (normally petrol) engine and the battery-powered motor powertrain. They are not as efficient as fully electric or plug-in hybrid vehicles.
   b) **Plug-in Hybrid Electric Vehicle (PHEV):** Also uses both, the internal combustion engine and the battery charged from an external socket (with a plug). So, the car´s battery can be charges with electricity rather than the engine. They are more efficient than HEV.
3) **Fuel Cell Electric Vehicle (FCEV**): Electric energy is produced from chemical energy, as for example a hydrogen FCEV.

In the next figure the three types of them are shown whit their different architecture.

[4] Cf. Charge wizard (What are the different types of electric vehicles?) 2021.

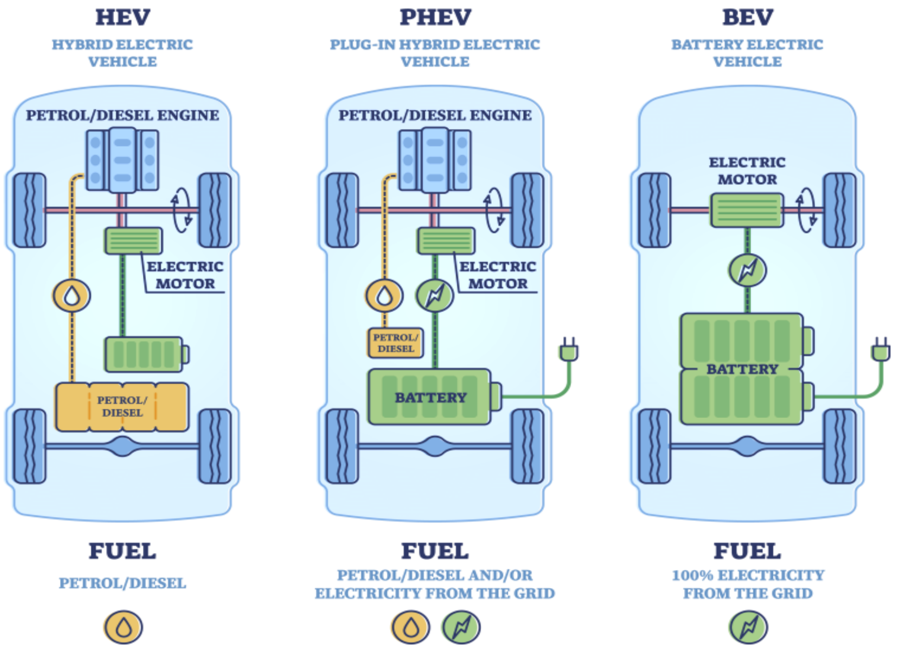
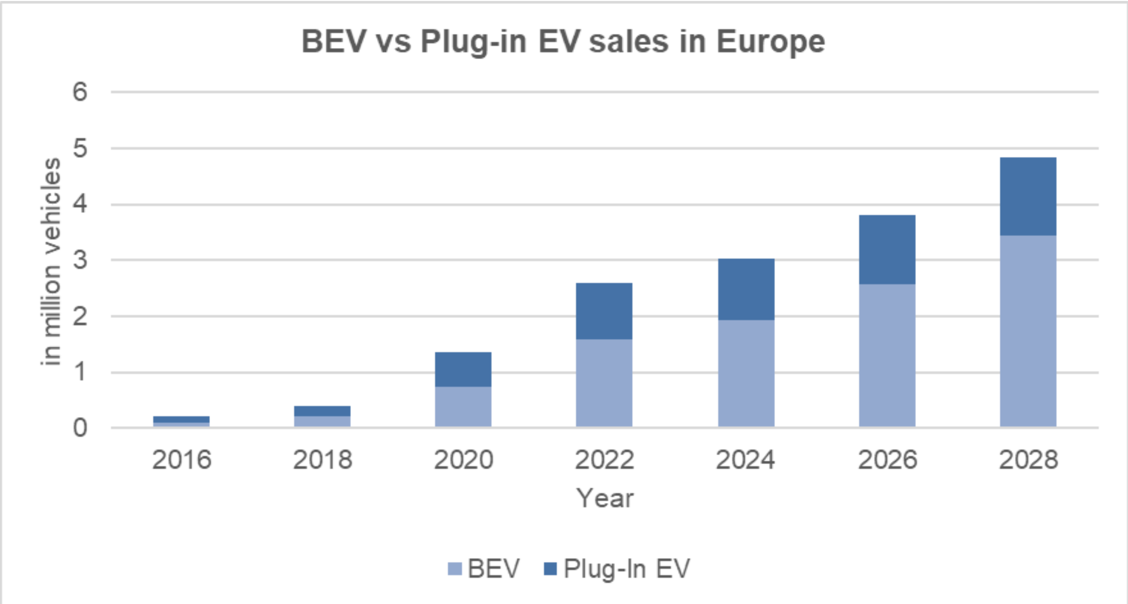


Figure 1: System architecture of the different electric cars[5]

Nowadays, the FCEV are not as important as the BEV or the HEV, however new trends show that this type of electric vehicles will have an important role in the future, especially with the use of hydrogen as a booster.



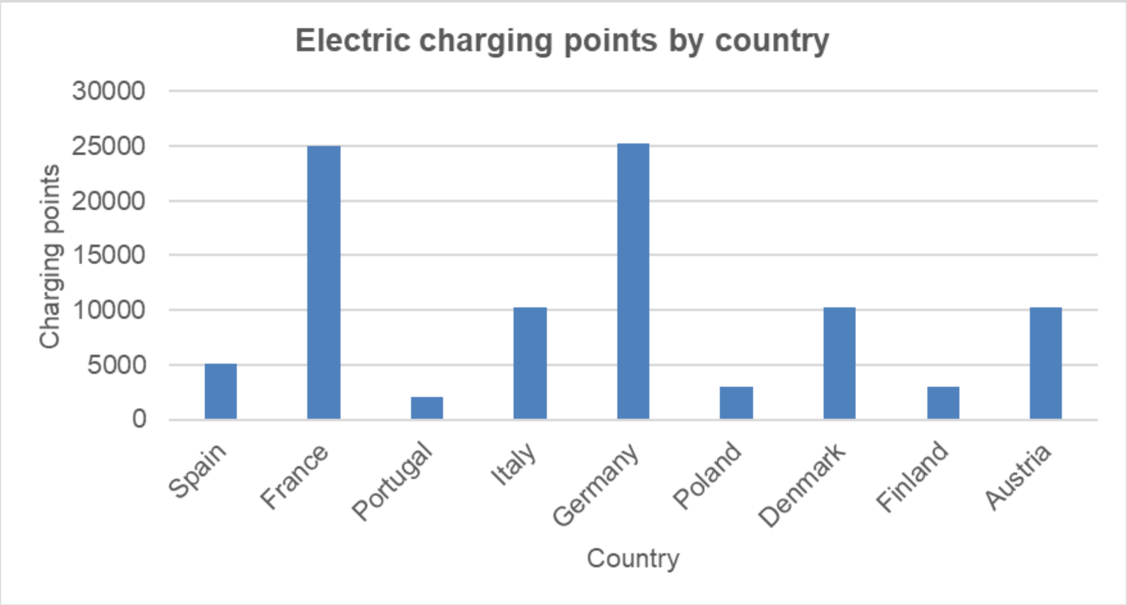
Graphic 2: Different types of electric vehicles sales in Europe[6]

As it is shown in the figure above, sales of EVs will be increased more and more in the coming years. To achieve this, is clear that proper energy management is of vital importance for the operation of EVs and a challenging research field that includes the

[5] Cf. Charge wizard (What are the different types of electric vehicles?) 2021.
[6] Cf. Statista Market Insights. May 2023.

design and implementation of efficient charging schemes that can ensure fast and reliable EVs charging to increase the vehicle autonomy.

However, the first thing that often comes to mind when discussing EVs is how the charging process will work and whether it's a worthwhile investment to switch to an electric car at this moment. In response to these questions, many efforts are being directed towards the expansion of charging stations and related infrastructure. In 2021, was estimated that 3.3 million units of charging points were able between Europe and North America[7], and in this field, Tesla is one of the more advances, with more than 40.000 supercharged stations around the world[8].



Graphic 3: Electric car charging points across different countries in the EU[9]

Furthermore, a very promoted and challenged technology on the EVs are the autonomous vehicles (AVs). They are defined as any type of vehicle where all mechanical-related procedures can be performed with limited or no human iteration. Mainly, there are two types of them[10]:

1) **Semi-autonomous:** the car can accelerate, brake and steer but the driver is still required and is still in full control.
2) **Fully autonomous**: they monitor roadway conditions and perform safety-critical task throughout the duration of the trip with or without a driver present.

Nowadays, the autonomous driving of smart vehicles has attracted scientific interest and the concept of electric smart grids is shifting towards standardization and

[7] Cf. ACEA (Driving mobility for Europe) (Distribution of electric car charging points across the EU) 2020.

[8] Cf. Tesla Company (Supercharger stations across the world) 2023.

[9] Cf. Journal of Energy Storage (Integration electric vehicles as virtual power plants: A comprehensive review on vehicle-to-grid (V2G) concepts, interface topologies, marketing and future prospects) 2022.

[10] Cf. Centre for sustainable systems (Autonomous Vehicles Facsheet) 2022.

development. Independent vehicles can perform various operations like delivery packages to elder people. To achieve this, the establishment of a reliable wireless link is of primary importance for reducing fatal accidents and traffic congestion.

In this area, the vehicle-to-grid (V2G) approach aims to optimize the way of transport, use and production of electricity by turning EVs into virtual power plants[11]. V2G refers to a bidirectional flow system operation, in which plug-in battery electric vehicles communicate with a recipient and allow the reciprocal flow between the EV and the electric grid. With this EVs would store and dispatch electrical energy stored in networked vehicle batteries. This technology, also improves stability and reliability of the grid, regulates the active power, and provides load balancing by valley filling.

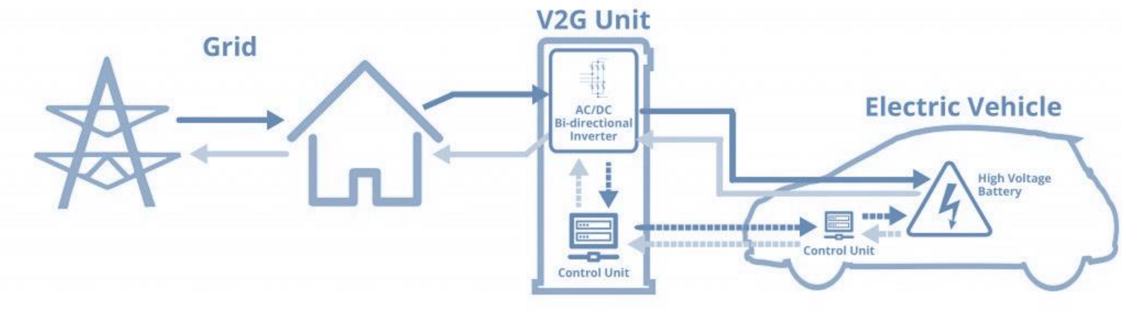


Figure 2: Schematic representation of V2G [12]

Several solutions have been proposed for integrating V2G technology and there are many challenges to come in this field as for example the mixing with the fifth generation emerging wireless infrastructures, for the mobile user to experience a unified approach on application management, for instance, a real time navigation with the traffic update.

In summary, the shift to EVs is gaining momentum for a more sustainable future. While BEVs are dominant, FCEVs may have a role in the future. EVs sales are increasing, and efficient energy management, charging infrastructure expansion, and battery advancements are crucial. Also, AVs are emerging, with potential for transformation, especially in conjunction with electric smart grids and V2G technology.

2.1 Sustainability in E-drive components

Nowadays, it is known that automotive firms are under growing pressure to address sustainability concerns arising from climate change and environmental degradation. The focus on sustainability should extend throughout the industry, not just in specific areas like research and manufacturing. To achieve this, companies should establish a central governance body responsible for driving sustainability efforts.

[11] Cf. Centre for sustainable systems (Autonomous Vehicles Facsheet) 2022.

[12] Cf. Cleantech Group (EV Charging: Software and Grid Services) 2019.

The industry has faced criticism for its high carbon emissions, harmful impact of rare earth metal demand, non-biodegradable waste, increased energy and water usage, and the substantial carbon footprint associated with car production. Implementing comprehensive sustainability measures is crucial for the automotive industry to meet the expectations of stakeholders and contribute to a greener future.[13]

Sustainability has become a crucial focus in vehicle manufacturing, making the study and improvement of electric drives even more significant. The table below highlights the differences of electric vehicles in comparison to conventional combustion vehicles with respect to different parameters.

Table 1: Differences between EVs and ICEs[14]

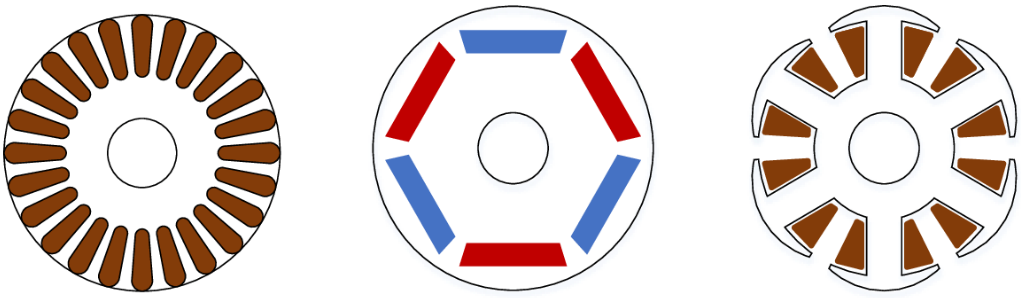
Parameter	Electric Vehicles (EVs)	Internal Combustion Engine vehicles (ICEs)
Energy saving	Low	High
Energy refilling	Slow	Fast
Environmental impact	Low	High
Energy efficiency	High	Low
Cost production	High	Low
Sustainability	Low footprint	High footprint

The table demonstrates that electric vehicles are an alternative to combustion engine vehicles, but they have not yet fully replaced them. Certain aspects, such as refiling or cost, still favor internal combustion engines. So, to establish electric vehicles as the optimal choice, there is a need for more innovative technology and sustainable approaches in component production.

Attending to the main topic of this thesis, the arching for the sustainability, in electric motors, the primary motor types utilized in EVs are the Permanent Magnet Synchronous Motor (PMSM), Externally Excited Synchronous Motor (EESM), and Induction Motor (IM). In the figure bellow the different schema of wireless excitation system dynamic model of this types of motor sis shown

[13] Cf. Standford Engineering. 2019.

[14] Cf. ResearchGate (On the Lightweight Structural Design for Electric Road and Railway Vehicles using Fiber Reinforced Polymer Composites-A Review) 2018.



(a) IM (b) PMSM (c) EESM

Figure 3: Schemas of wireless excitation system dynamic model [15]

Each of them has different advantages and disadvantages that makes it unique. For example, considering the weight, PMSM is the lightest, however that with also the compact design and the high efficiency, makes it the most expensive. Talking about the cost, as well as the EESM as the IM have a reduce cost and comparing these las two, IM have highest efficiency than EESM, because the last one has a simple construction and no permanent magnets.

Making an analysis and comparison of the types of motors mentioned before, the PMSM exhibits superior performance, however, the requirement of rare earth permanent magnets makes PMSM costly and demands maintenance. Currently, following the currents in favor of the search for sustainability and new designs to make it possible, what is known as new energy vehicles (NEVs) have grown. They prioritize factors like high efficiency, speed, low noise, vibration, and harshness and cost-effectiveness.[16]

To address these challenges, more research and development are necessary. Innovations in motor design optimizations, multi-physics simulation, improved cooling methods, and the development and application of new materials are crucial areas of exploration.[17]

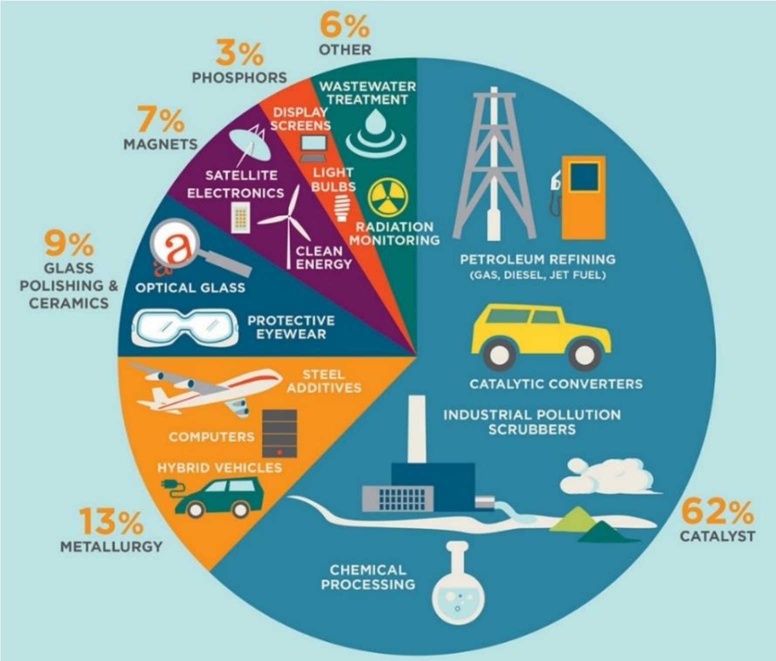
Focusing on the production of electric stators and rotors, it involves several stages, including the extraction of raw materials, their transportation, the manufacturing of the components, assembly, and transportation of the final product. Each of these stages has environmental important impacts. One of the main environmental concerns in the production of electric stators and rotors is the use of rare earth magnets (REM), particularly the NdFeB (Neodymium Iron Boron Magnets), crucial for high-performance and efficient electric motors. However, there is a lack of research on sustainable REM production, considering its wide range of applications and future usage. The extraction of REMs has various environmental, social, and economic impacts, including

[15] Cf. Semantic Scholar (Synchronous Machines with High-Frequency Brushless Excitation for Vehicle Applications) 2019.

[16] Cf. Carwale (Electric cars in India, nex electric vehicles) 2021.

[17] Cf. Cai (Review and Development of Electric Motor Systems and Electric Powertrains for New Energy Vehicles) 2021.

radioactive byproducts and the use of harsh chemicals. Strontium-ferrite magnets in synchronous reluctance motors are suggested as a more environmentally friendly alternative.



Graphic 4: Percentages in the use of REM[18]

Regarding this field, to reduce reliance on rare earth magnets in motor design, various challenges must be addressed, such as the risk of demagnetization and increased machine size to compensate for lost power. In this area, there are important innovative technologies developed, looking for the best way of electric drive train production in the most sustainable way. One example of it is the commercialization of switch reluctance motors (SRM), which have more advantages compared to conventional motors. They operate with one phase missing, have an instant stop mode for induction motor systems, and use copper wire instead of aluminum for lower resistance. SRM technology also effectively manages the skin effect, reducing conductor resistance by lowering the motor's operating temperature. Additionally, SRMs boast a high-power density and an excellent power speed range.

[18] Cf. Electronic Recycling (Rare earth minerals) 2021.

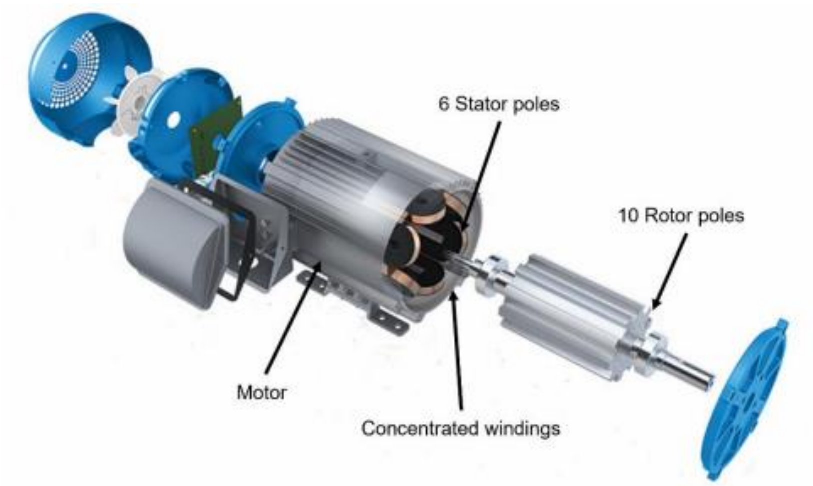


Figure 4: SRM architecture[19]

However, SRMs have the drawback of being challenging to control, leading to significant noise and vibration. The remarkable benefits of this technology include high efficiency, reduced torque ripple, and the elimination of the need for rare earth metals in motor manufacturing.

In the searching of an agile production system for an electric motor, there is a type of motor, which consist in the PMSM with a hairpin technology (HP). The production of the electric traction motors is divided into three main subdivisions, which are rotor production, stator production and final assembly. In this area, the chair of Production Engineering of E-Mobility (PEM) at the RWTH Aachen University is working on a project called HaPiPro[2] [20], which is the main product that is studied in this thesis.

Because of this, some of the most important companies as for example Mercedes Benz, are taking measures to improve the performance of these engines. For example, with the implementation of axial flow engines[21]. However, when designing an electric motor for EVs some challenges must be taking into careful consideration, as for example, high robustness, acceptable cost, high level of reliability and the use of the advance control methods. And the most important ones, the high efficiency performance at all speed and torque ranges and a good voltage regulation needed over a wide speed.

To face these challenges, there were developing many types and technologies of motors used in EVs, for example, DC drives, induction Motors (IM) or permanent magnet (PM). Each of them has different advantages and disadvantages but all should be designed to their best to overcome most of EVs drive challenges. As an additional

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[19] Cf. Turntide (Motors - Turntide Technologies) 2022.

[20] Cf. RWTH (Chair of Production Engineering of E-Mobility Components (PEM)) 2020.

[21] Cf Green Car Congress (Mercedes-Benz to manufacture YASA axial-flux electric motors in Berlin) 2021.

information, the model Fiat Panda Electra is using the DC motor and Toyota Prius model the PM.

Moreover, it is also important to focus not only on the different new designs of electric motors but also in the manufacturing and operations that their production involves and its consequence in the supply chain. In these areas, there are some topics to deal with:

- **Manufacturing and operations:**
    a) **Sustainable Manufacturing**: The implementation of maintenance, quality, and production procedures is essential in sustainable manufacturing. This helps in improving material recycling and reusing, leading to reduced waste.
    b) **Recycling and End-of-life Disposal:** Providing easy returns and recycling options for customers allows them to return products for proper disposal when they reach the end of their life.
    c) **Sustainable Power Procurement:** Opting for renewable energy sources for power procurement helps in reducing the environmental impact of operations.
- **Supply Chain:**
    a) **Environmentally Friendly Supply Chain:** Introducing eco-friendly practices in supply chain activities such as logistics, distribution, warehousing, and inventory management.
    b) **Responsible Sourcing:** Ensuring the environmentally responsible sourcing of metals, materials, and products used in the production process.
    c) **Due Diligence:** Conducting thorough assessments to ensure that all material and product procurement processes adhere to environmental and ethical standards, independently.

Apart from this, once the product has been manufactured, there are other issues to consider, such as sales and marketing, and of course in these areas the search for sustainability also has a key role. This involves programs like retrofitting to reduce emissions, improving the efficiency of older vehicle models, and restoring worn-out parts of cars.

As well as the modern technologies and designs, and the process to achieve this, are involved in what is now known as the circular economy. The circular economy is an economic system designed to be restorative and regenerative, maximizing the use of resources. It emphasizes the reuse of materials instead of the traditional "single-time-use" manufacturing cycle.[22] In the context of the electric vehicle, currently only 15% of

[22] Cf. European Parliament (Circular economy: definition, importance and benefits) 2023.

original equipment manufacturers (OEMs) have an electric vehicle (EV) strategy that includes the use of renewably powered charging infrastructure. A workable sustainable business strategy could involve integrating residential batteries, solar energy, and electric automobiles.

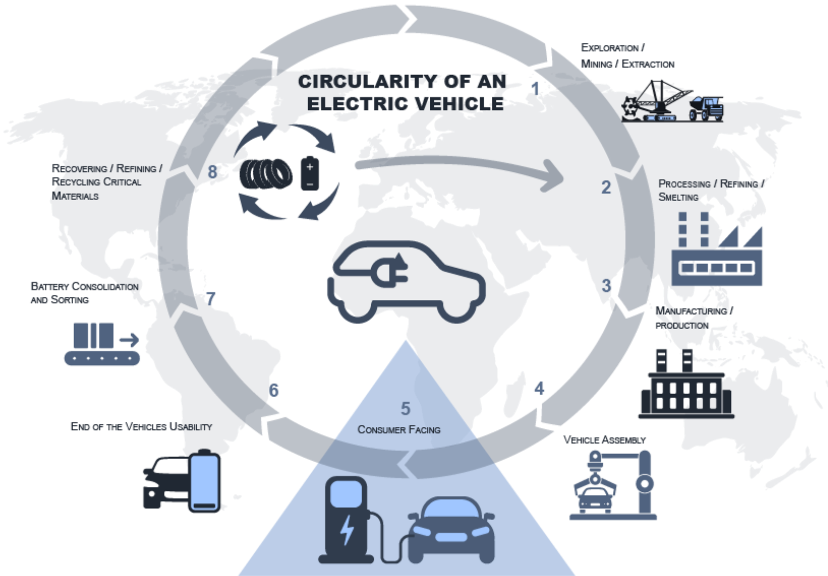

Figure 5: Circularity of an electric vehicle[23]

To achieve this, automobile groups would need to collaborate more closely with utilities and the government. BMW's collaboration with Pacific Gas & Electric Company for their "Charge Forward" pilot program exemplifies this approach. Incentives and changes in consumer behavior encouraged most participating EV owners to charge their cars during the day when there was excess solar power. Other viable models, such as leasing and embracing the circular economy principles, can significantly improve the overall positive impact of electric vehicles compared to internal combustion engine vehicles.

Moreover, another approach to sustainable production, is the use of renewable energy sources in the manufacturing process, for example at the BMW Group plant in Leipzig, production is supported by wind turbines and is also the first automotive plant in the world to pilot a newly developed burned technology in its paint shop that can also use hydrogen[24].

To sum up, to achieve sustainability goals, it is crucial for the automotive industry to give equal importance to all aspects mentioned earlier. However, there is a noticeable imbalance in prioritization. Sustainable manufacturing and product development, while supporting the circular economy receive the highest attention, while sales, marketing

[23] Cf. ERM (Building the connected EV) 2022.

[24] Cf. BMW Group (BMW Group Leipzig Plant) 2022.

and mobility services are given the least priority. This skewed focus indicates that the industry tends to concentrate more on areas closer to its core competencies.

2.2 Sustainability analysis in e-drive technology

Life Cycle Assessment (LCA) is a widely tool in the field of sustainability that evaluates the environmental impact of a product through its entire life cycle, from raw material extraction to end-of-life disposal[25]. However, as everything in the current world, the functioning of LCAs in the electric drive sector, has been improving during the last years. For example, in the field of the data availability and accuracy new databases and models have been developed, such as OpenLCA software, which will be used in this thesis.

In the last years, this tool was used to describe the difference between the EVs and the internal combustion engine vehicle (ICEVs). As an example, in a study, a comparative LCA of an electric vehicle and an internal combustion engine vehicle using the appropriate power mix: the Italian case study was developed.[26] The purpose of the study was to compare the performances of two passenger cars: an electric vehicle (EV) and an internal combustion engine vehicle (ICEV) paying particular attention to the production of electricity that will charge the EV.

The study acknowledges that electricity production is the primary cause of environmental impacts for externally chargeable vehicles and emphasizes the importance of accurately estimating the impacts associated with the electricity used to charge a growing fleet of electric vehicles (EVs). Instead of using hypothetical or average power mixes, the study aims to identify the actual power mix that will supply energy to EVs, considering their electricity demand as an additional factor. The geographical location plays a significant role not only in determining the power mix but also in influencing driving behavior. For this research, Italy is the focus of attention.

To gain insight into future scenarios, which can be more informative than the current limited market penetration of EVs, the analysis is conducted for two different time horizons: 2013 and 2030. Despite the increasing presence of renewable energy sources in the national power system, the study shows that the electricity used to charge EV batteries is currently and likely to be primarily produced from fossil fuels. However, in both the 2013 and 2030 scenarios, As can be showed in the figures bellow with the results., EVs demonstrate better environmental performance in impact categories they are expected to improve, such as air pollutant emissions related to air

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[25] Cf. Ecochain (Life Cycle Assessment (LCA) – Complete Beginner's Guide) 2021.

[26] Cf. Modern individual mobility (A comparative LCA of an electric vehicle and an internal combustion engine vehicle using the appropriate power mix: the Italian case study) 2015.

acidification, photochemical oxidant formation, and particulate matter formation potential.

Impact categories	Unit	EV	EV+	ICE_gasoline
CED nonrenewable	MJ	368,480.7	415,490.5	697,203.24
CML2001 air acidification	g eq. SO_2	80,678.38	94,064.87	132,262.95
CML2001 depletion abiotic resources	kg eq. Sb	189.6437	214.0148	318.7499
CML2001 eutrophication	g eq. PO_4	35,989.7	43,126.02	28,359.595
CML2001 human toxicity	g eq.1,4-DCB	20,538,605	25,608,144	14,219,070
IPCC2007 greenhouse effect	g eq. CO_2	23,264,509	26,461,833	46,208,980
ReCiPe photochemical oxidant formation potential	g eq. NMVOC	63,239.25	70,233.52	107,666.08
ReCiPe particulate matter formation potential	g eq. PM10	31,653.61	35,665.71	41,429.264

EV+ is the EV with a higher energy consumption (22 kWh/100 km rather than 19 kWh) and with shorter battery life (100,000 km rather than 150,000)

Figure 6: LCIA results for 2013 scenario (complete vehicles lifetime-150.000 km)[27]

Scenario 2030	Unit	EV 2030	EVPV36	EV_PV_50	EVLB	ICEV
CED nonrenewable	MJ	354,880.74	278,385.58	248,637.47	349,828.22	568,829.85
CML2001 air acidification	g eq. SO_2	61,353.16	56,847.57	55,095.40	57,426.53	111,444.21
CML2001 depletion abiotic resources	kg eq. Sb	193.98	150.87	134.10	191.24	261.63
CML2001 eutrophication	g eq. PO_4	29,320.57	29,638.84	29,762.62	26,430.31	25,441.66
CML2001 human toxicity	g eq.1.4-DCB	19,691,367	19,550,393	19,495,570	17,357,927	12,863,494
IPCC2007 greenhouse effect	g eq. CO_2	22,332,799	17,271,631	15,303,400	21,964,550	37,426,347
ReCiPe photochemical oxidant formation potential	g eq. NMVOC	54,542.36	50,028.73	48,273.43	52,931.92	91,097.32
ReCiPe particulate matter formation potential	g eq. PM10	27,284.58	25,860.25	25,306.35	26,026.33	36,335.97

EVPV36 is the scenario with 36 % of energy of EV recharging from PV, EVPV50 with 50 % from PV and EVLB is the baseline EV but with a 25 % lighter battery (164 kg instead of 218 kg)

Figure 7: LCIA results for 2030 scenario (complete vehicles lifetime-150.000 km)[28]

Notably, the major contributions to these impact categories by EVs are from the electricity and car production life cycle, meaning that these pollutants are emitted far from densely populated areas.

As a conclusion, the study realised that EVs have a significant impact on air pollution and emissions due to electricity and car production. Despite using fossil-fuel-produced electricity, EVs still have lower greenhouse effect and energy consumption compared to gasoline-powered ICEVs. However, there's a trade-off with categories like eutrophication and human toxicity, mainly due to toxic battery manufacturing emissions. Renewable energy sources improve EV performance in some categories, but not in eutrophication and human toxicity. A battery production evolution by 2030 may reduce these impacts. Other factors affecting human health include air acidification, oxidant formation, particulate matter emissions, and greenhouse effect.

[27] Cf. Modern individual mobility (A comparative LCA of an electric vehicle and an internal combustion engine vehicle using the appropriate power mix: the Italian case study) 2015.

[28] Cf. Modern individual mobility (A comparative LCA of an electric vehicle and an internal combustion engine vehicle using the appropriate power mix: the Italian case study) 2015.

Currently, LCAs are commonly also used to assess the environmental impact not only of the whole vehicle, but also of the production and use of electric motors, including their stators and rotors. In a study a Comparative life cycle assessment of motors for electric vehicles was made [29], comparing the LCA of different types of electric motors such as the PMSM, the Sensing Diagnostic Module Motor (SDM) and the SRM, introduced in the section before, to achieve conclusions about the environmental impact of each. Founding that the Asynchronous Motors (ASM) and the SRM have lower environmental impact overall, with the ASM having the lowest.

Another study called Comparative LCA of electric motors with different efficiency classes[30] was showing the dominance of the use stage in the motor's life cycles and that an increase in efficiency pay off environmentally within the first month of operation in the applied load-time profiles. And, that the increase of the analysed motors efficiency encompasses trade-offs between the stage's materials, manufacturing, and end-of-life versus the use stage regarding toxicity and metal resource.

Moreover, attending the importance of the circular economy in the electric drive sector, LCA has evolved to include the assessment of the environmental benefits such as the recycled materials in battery or motor production, as was mentioned before. All this leads to the search of the standardization of LCA methodologies in the electric drive sector, to ensure consistency and comparability of results.

Overall, the state of the art in electric drive technology is promising, with ongoing advancements in battery technology, motor technology, increase in the number of charging stations... As electric vehicles become more widespread, it is likely that the people will continue to see innovation and improvements in electric drive technology in the years to come.

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[29] Cf. Journal of Cleaner Production (Comparative life cycle assessment of conventional combustion engine vehicle, battery electric vehicle and fuel cell electric vehicle in Nepal) 2022.

[30] Cf. The International Journal of Life Cycle Assessment (Comparative life cycle assessment of electric motors with different efficiency classes: a deep dive into the trade-offs between the life cycle stages in eco-design context) 2017.

3 Definition of the target space and identification of objectives

In this section, it will be determined the specific focus and boundaries of this project. Identifying the key aspects and variables that are going to be investigated or assess.

As the world transitions towards a more sustainable future, the production of electric drives has emerged as a key area for investigation, including electric motors, batteries, and power electronics, integral components of electric vehicles and the use of renewable energy systems.

Assessing the environmental impact of electric drive production is essential to understand the sustainability performance of this technology. This master's thesis aims to define the target space by utilizing the $HaPiPro^2$ project database, which provides valuable data and insights, to conduct a comprehensive LCA for electric drive production. The LCA will encompass various stages, from raw material extraction to end-of-life treatment, and will assess key aspects such as energy consumption, ecosystem quality and resource usage.

By defining the target space, this thesis aims to identify areas of improvement and guide decision-making towards more sustainable practices in electric drive production.

3.1 $HaPiPro^2$ Project

This project is a research initiative conducted by the Production Engineering of E-Mobility Components Institute (PEM) for Production Engineering and Machine Tools at RWTH Aachen University, which aims to advance the production processes of electric drives and make them more efficient sustainable and cost-effective. The main object is to conceptual design and testing of manufacturing, production, and process designs for hairpin stators that are optimal in terms of variation flexibility and process stability.

The research work will determine the dependencies such as different wire thicknesses on the production process and technology. It will also increase process flexibility and stability by identifying relations between product features and process parameters [31].

Some of the more important key objectives of the $HaPiPro^2$ project are showed below:

- **Sustainable manufacturing:** strives to develop sustainable manufacturing methods for electric drives and improve energy efficiency throughout entire production life cycle.
- **Process optimization and automation:** $HaPiPro^2$ aims to enhance production processes by implementing optimization and automation

[31] Cf. RWTH (Chair of Production Engineering of E-Mobility Components (PEM)) 2020.

techniques. This helps to reduce the production time and cost associated with the electric drive manufacturing.

- **Life Cycle Assessment (LCA):** the project use LCA methodologies to evaluate and minimize the environmental impact of electric drive production. The energy consumption, emissions and resource usage are considered to ensure sustainability.
- **Collaboration and knowledge exchanger:** the project also promotes collaboration among industrial partners, research institutions and experts. This collaboration facilitates knowledge exchange and fosters innovation in the field of electric drive production.

With this objective, the sustainable development and advancement of the electric drive production processes is supported, and by implementing sustainable practices, optimizing processes, conducting LCAs and fostering collaboration, contributes to a greener and more energy-efficient transportation sector.

The important section for this master thesis is the sustainability of the entire life cycle of the reference product Hairpin-Stator, which is investigated as part of the $HaPiPro^2$ project. In this context, the limitations should be determined. The main objective of this sustainability assessment is to analyse the impact of the stator $HaPiPro^2$, on social and ecological sustainability. The assessment aims to quantify the effects and evaluate their connection to sustainability.

Furthermore, in the upcoming sections, the attention will be directed toward evaluating the product and the current data landscape to pinpoint gaps and assess the quality of available data.

3.2 Analysis of the product and the production process

To start, the reference product should be described. It is called automotive stator HaPiPro[2], and is manufactured in the Ford plant in Cologne, as part of the project with the objective to optimize the production processes of hairpin stators. The dimensions of the stator are 190mmx245mm and the finishes stator, according to the component drawing, it is composed by the following materials:

Table 2: Material of the hairpin stator[32]

Material	Volume
Cooper	1.043.280 mm³
Insulation paper	85.489 mm³
Electric sheet metal	1.876.698 mm³

In the figure below it is finding a schema of the structure of a hairpin stator. With the different parts of it, as the connection terminal, the contact ring, the hairpin basket, and the insulation paper just before the biggest lawyer, the laminated sheet metal package.

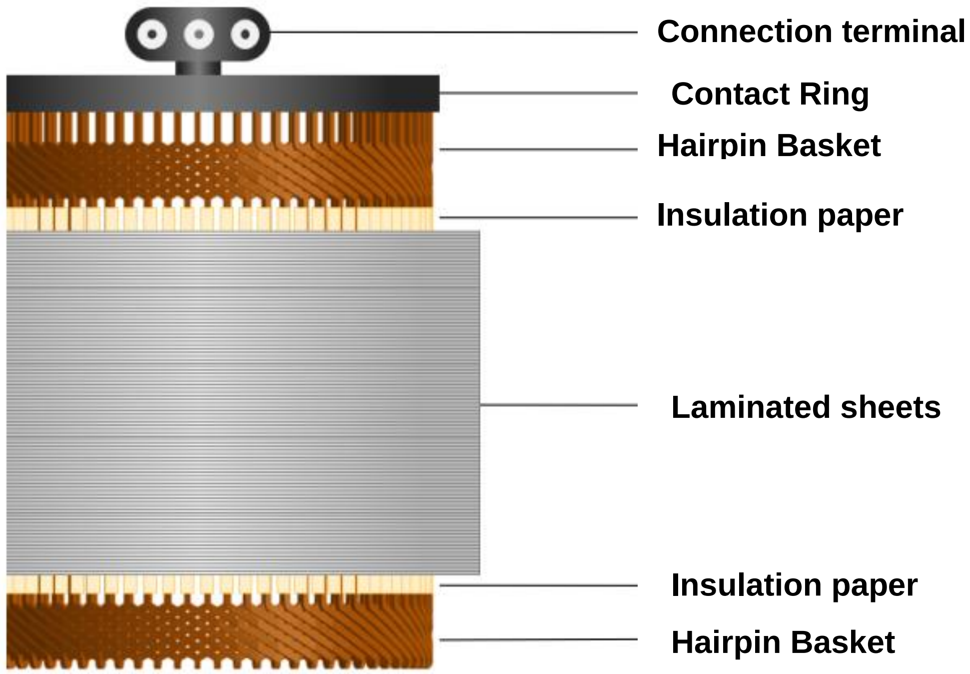

Figure 8: Hairpin stator structure[33]

[32] Cf. RWTH (Chair of Production Engineering of E-Mobility Components (PEM)) 2020.
[33] Cf. RWTH (Chair of Production Engineering of E-Mobility Components (PEM)) 2020.

The process of production it Is showed in the figure bellow, and it is separated between the production of the cooper flat wire, and the production of the electrical sheet package

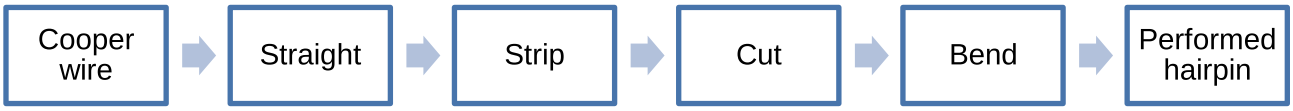

Figure 9:Process of hairpin basket production[34]

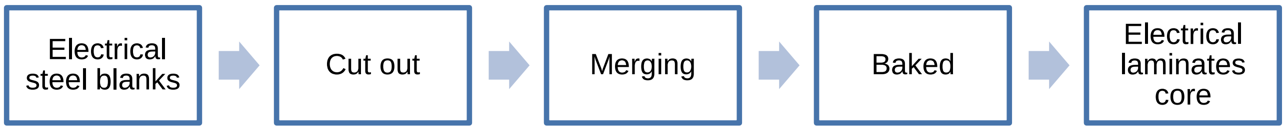

Figure 10: Process of the electrical sheet package production[35]

The first one involves copper flat wire, which is initially painted and delivered in rolled-up form. The wire is straightened to achieve the desired shape for hairpins. Then, the wire's insulation made of polyamidimid94 is removed to enable subsequent contacting operations. The volume of the lacquer insulation is approximately 286.793 mm³. The flat wire used is sold under the trade name SHTherm® 220 by Schwering & Hasse Elektrodraht GmbH. The copper wire is cut and bend into specific hairpin shapes, assuming no loss in the process. The copper portion of the stator corresponds to the supplied copper quantity. In the figure bellow the process is shown.

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[34] Cf. RWTH (Chair of Production Engineering of E-Mobility Components (PEM)) 2020.
[35] Cf. RWTH (Chair of Production Engineering of E-Mobility Components (PEM)) 2020.

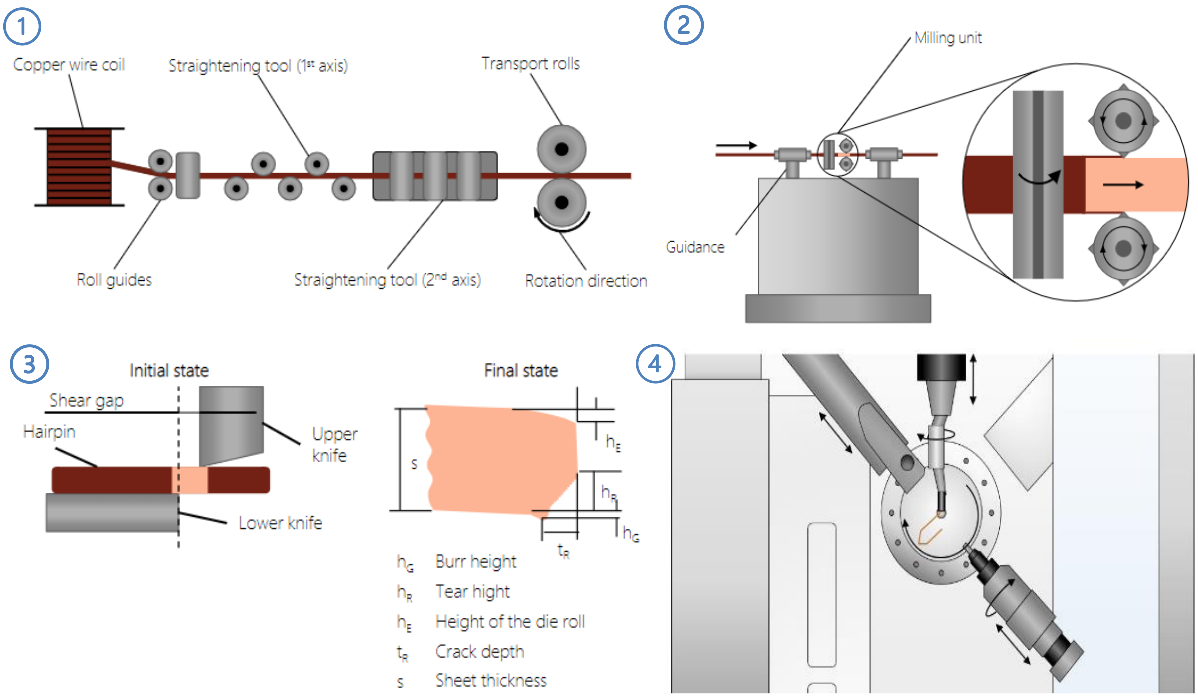

Figure 11: Cooper transformations for the hairpin basket production[36]

The second process involves the production of an electrical sheet package. The input for this process is electrical sheet blanks with dimensions of 2000 mm x 1000 mm x 0.5 mm. These blanks are used to cut out required contours using a laser cutting machine, including grooves. The individual electrical sheets, each 0.5 mm thick, are then stacked and joined together. In the final step, the stacked sheets are baked in a furnace to form an electrical sheet package. During the contour cutting, material waste is generated and cannot be used further. With a required height of 160 mm, 320 blanks are needed. If 50 blanks can be produced from each electric sheet blank, a total input quantity of 6.400.000 mm³ of electrical sheet is required. The electrical sheet has a density of 7.6 kg/dm³ and is coated with an insulating lacquer. The specific composition of the lacquer is unknown.

[36] Cf. RWTH (Chair of Production Engineering of E-Mobility Components (PEM)) 2020.

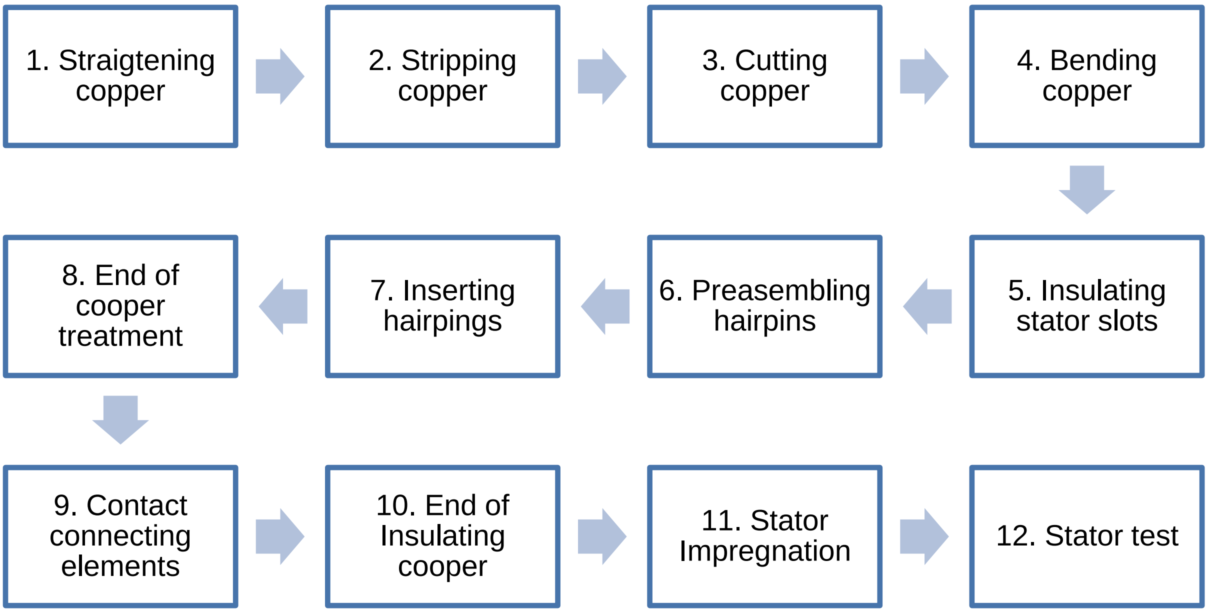

Figure 12: Hairpin stator, production process chain[37]

In the process chain, groove insulation paper is used to separate the hairpins from the electrical sheet package, as it is shown in the figure bellow. The insulation paper, made of synthetic polyaramid polymer called DuPont's Nomex® 410, is unwound, folded, cut, and pressed into the pre-milled grooves using compressed air. It has a thickness of 0,18mm. The sustainability assessment assumes no issues with the production of insulation paper. The quantity of groove insulation paper used is considered as an input variable for the production process.

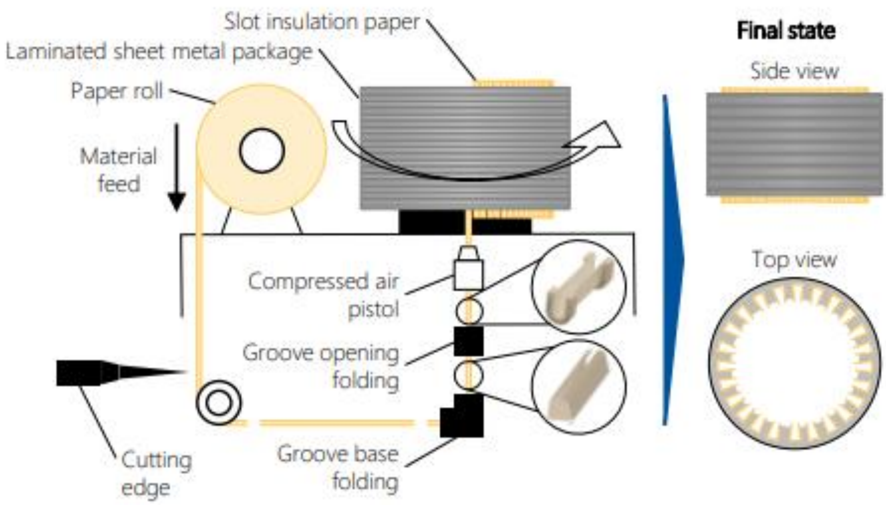

Figure 13: Insulating stator slots phase on the hairpin stator production[38]

The hairpins are assembled into a hairpin basket and inserted into grooves lined with insulation paper, as it is shown in the figure bellow. The ends of the hairpins are

[37] Cf. RWTH (Chair of Production Engineering of E-Mobility Components (PEM)) 2020.
[38] Cf. RWTH (Chair of Production Engineering of E-Mobility Components (PEM)) 2020.

released and restricted together, ensuring proper contacting. Variations in hairpin length are compensated for by aligning the ends with a cutting element. Copper losses during this step are considered negligible and not factored into the sustainability assessment.

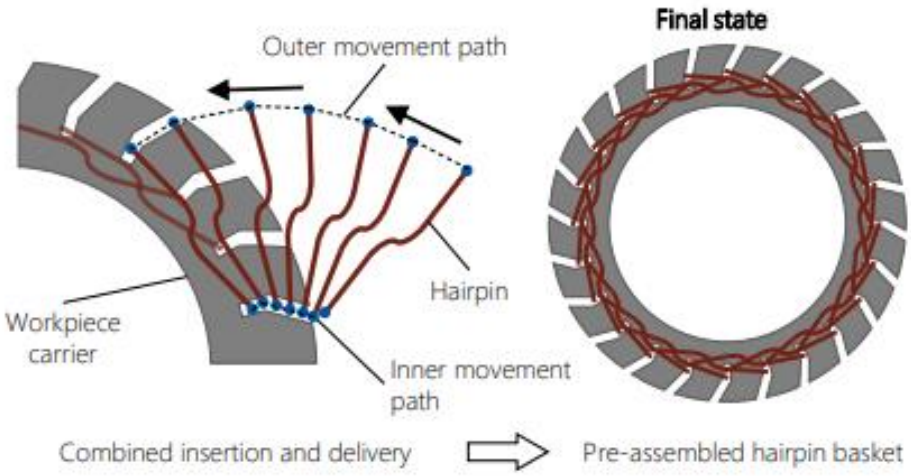

Figure 14: Pre-Assembling hairpins phase on the hairpin stator production[39]

After contacting the hairpins, wiring elements such as contact rings, jumpers, connection terminals, and star connectors are mounted. However, these elements are not included in the sustainability assessment and are only listed for process visualization. To prevent short circuits, a powder coating of resin is applied to the bare copper ends that make contact. Approximately 56 mm³ of powder coating is required per contact point, with a total of 144 contact points to be coated. The product used for the coating is ResiCoat e-lock® from AkzoNobel.

In the final production step, as it is showed in the figure bellow, the stator grooves and winding core are impregnated with a resin known as drip resin. This resin, such as Voltatex 4200®, is used to enhance properties like heat dissipation. Approximately 6 kg of dripping resin is needed per stator.

[39] Cf. RWTH (Chair of Production Engineering of E-Mobility Components (PEM)) 2020.

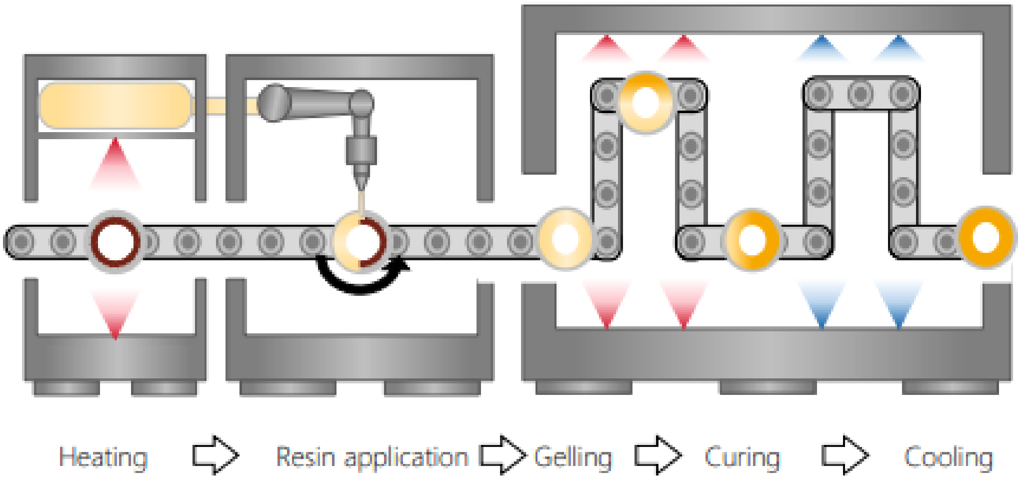

Figure 15: Stator impregnation phase in the hairpin stator production[40]

When the stator is finally produced, it is tested at the end of the production line. During this process the insulation strengths, the resistance and the polarization index are tested.

Once the process of production is described, it allows to define the target space for the development of the LCA for the hairpin stator defined and the creation of new data to study, however before defining the target space, it is important to make a distinction between the three main types of product life cycles [41] which can be find it on the figure below and are defined like:

1) **Cradle-to-gate** refers to the carbon impact of a product from the moment it's produced to the moment it enters the store. Some companies prefer to measure cradle-to-gate because they've designed a product that can be easily recycled or composted, avoiding the landfill altogether.
2) **Cradle-to-cradle:** focuses on assessing the environmental impact of the product from its raw material extraction stage (cradle) to the point of its completion at the manufacturing facility or factory gate. This approach typically includes the following stages: Raw material extraction and manufacturing process. This approach in the context of the hairpin stator, provides valuable insights into the environmental performance of it up to its completion but does not consider the subsequent stages of the product's life cycle.
3) **Cradle-to-grave:** considers the entire life cycle of the product, from its raw material extraction (cradle) to its final disposal or end-of-life stage (grave). This approach includes the cradle-to-gate stages mentioned above and further expands to encompass, such as use phase and the end-of-life management.

[40] Cf. RWTH (Chair of Production Engineering of E-Mobility Components (PEM)) 2020.

[41] Cf. Ecochain (Cradle-to-Gate: What is it and How does it work in LCA?).2021.

By adopting the cradle-to-grave approach, a more comprehensive understanding of the environmental impact of the hairpin stator can be achieved, considering the entire life cycle, including resource extraction, manufacturing, use, and disposal stages.

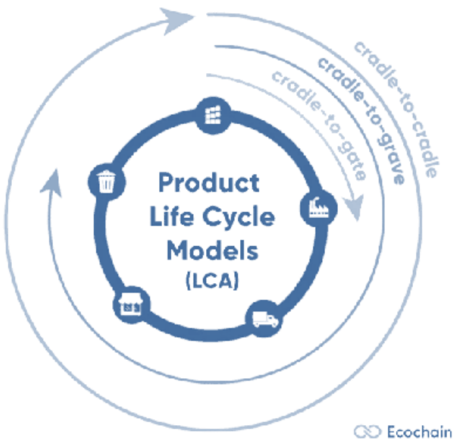

Figure 16: Cradle-togate vs Cradle-to-Grave method [42]

After analyzed them, in the context of this thesis, the cradle-to-grave it is the appropriated to be used, because it enables to identify opportunities for improvement and make informed decisions regarding the environmental sustainability of the product.

For a better overview, the LCA is divided into four main areas, which are showed in the figure bellow, including from the extraction of the raw materials until the management of the end of the product life. However, as the main objective of this thesis is to analyse the production process of the hairpin stator, The life cycle that is going to be carried out will focus on the first two stages, from the extraction of the raw materials to the manufacturing process, without making greater emphasis on the stage of product use and the management of the end of life.

In the further course of the sustainability assessment, the individual main areas are modeled and considered independently of each other, and the inputs and materials used will be described in the next section with the develop of the LCA in the OpenLCA software.

[42] Cf. Ecochain (Cradle-to-Gate: What is it and how does it work in LCA?) 2021.

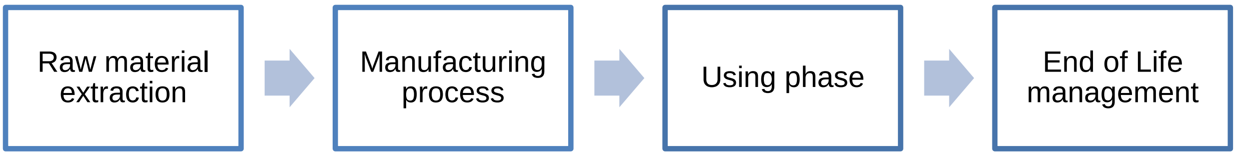

Figure 17: LCA stages of the hairpin's stator LCA [43]

3.3 Data acquisition and collection using Eco-invent data base

For the data acquisition the resource use it is the Eco-invent Database, which is a Lice Cycle Inventory (LCI) that supports various types of sustainability assessments.[44] This one provide to the users with a comprehensive understanding of the environmental impacts associated with their products and services.

It serves as a folder covering a wide range of sectors in the global and regional scales. In the nowadays, it encompasses over 18.000 activities, which represents various human activities or processes. These Eco-invent datasets contain valuable information about the industrial or agricultural processes which are modeled including the natural resources extracted from the environment, the emissions released into water, soil and air, the products required from other processes (for example the electricity) and the products, co-products and wastes generated.

As is important for the studies of the impact, each activity in this Database is attributed to a geographic location, using the compressed name of each (for example for Germany it is used GE). As the Eco-invent Database is a background database, which means that is maintained by various organizations, government agencies and privates' companies with the purpose of storing and organizing data relevant to conducting background checks, the aim is cover activities in the most relevant geographies for the selected product or service.

For each data set in the Eco-invent Database Life Cycle Impact Assessment (LCIA) scores for several impact assessment methods and impact categories, in the table below some of them are shown.

[43] Cf. RWTH (Chair of Production Engineering of E-Mobility Components (PEM)) 2020.

[44] Cf. Eco-Invent Database.

Table 3: Assessment methods and Impact categories in the Eco-invent Database[37].

Assessment methods	Impact categories	
IPCC 2021	Climate change	
EF v3.1	Human toxicity	
ReCiPe	Water Use	Land Use

The data shared for this thesis, has different documents, each have distinctive characteristics since each of them use a different type of analysis, in the sections bellow it is discussing the one to use in that case and why it is appropriate for it.

3.4 Discussion of the Eco-invent data base approach

The choice of approach to gather data normally depends on the specific objectives of the study and the question that want to be answered with the life cycle assessment. Each approach has its advantages and disadvantages, and the decision will depend on the scope and level of detail you want in your analysis. Some characteristics of each are shown below:

1) **Accumulative Pseudo-Static (APos):** This approach is appropriate if looking for a broad understanding of the cumulative impacts up to the present moment without considering the future implications of actions. It provides a rapid and straightforward evaluation of the current state of the hairpin stator's life cycle, though it does not consider how present decisions may influence future impacts.
2) **Consequential Accumulative (CApos):** Aim for a thorough and realistic evaluation of impacts throughout time, this approach is better suited. CApos consider causality and the long-term consequences of present actions, offering a more precise understanding of how current decisions can shape future and cumulative impacts. It proves particularly valuable when analyzing choices or decisions that could have significant ramifications throughout the life cycle of the hairpin stator.
3) **Cut-off Accumulative:** Focuses on considering only the impacts that occur up to a certain cut-off point in time. In other words, it analyzes the cumulative impacts of a product or system only until a specific moment and disregards any impacts that might occur after that point. This approach is also known as the "Snapshot LCA" since it takes a snapshot of the system at a particular moment in time.

In summary, if there is the possibility to conduct a more detailed and comprehensive analysis, the consequential accumulative approach (CApos) is preferable, as it considers causality and long-term consequences of actions, not as the Cut-off

Accumulative which stops the analysis at a certain point in time. However, in the context of this master thesis, the approach selected it is the Cut-off Accumulative, and bellow it is explained why.

The rationale for using the "Cut-off Accumulative" approach in the creation of an LCA for a hairpin stator can be based on various factors:

1) **Resource and Time Constraints**: Performing a comprehensive life cycle assessment for a product can be a resource-intensive and time-consuming task. In this case, where there are limited resources or time available, a cut-off approach can be adopted to quickly obtain results focusing on the earlier stages of the life cycle, like the raw material extraction.

2) **Relevance to Decision-Making**: As the LCA it is focusing on the first two stages, the raw materials extraction and the manufacturing, some decisions or environmental impacts might primarily occur during these two earlier stages of the product's life cycle. So, analyzing the impacts only up to the point where significant decisions are made can be relevant.

3) **Focus on Hotspots**: The cut-off approach can help identify "hotspots" in the life cycle of a hairpin stator by revealing the stages with the most substantial environmental impacts up to the cut-off point. This information can be valuable for prioritizing improvement efforts.

4) **Data Availability**: Finally, the data for later stages of the hairpin stator´s life cycle (e.g., disposal or end-of-life) might be less accessible or more uncertain. Using the cut-off approach allows the analysis to focus on data that is readily available and more reliable.

However, it's essential to note that the cut-off approach comes also with some limitations, because by excluding the impacts that occur after the cut-off point, it might miss important impact that happen during the use phase or end-of-life of the hairpin stator. Therefore, it's essential to clearly define the cut-off point, which in this thesis it is determined in the final stage of the production of the hairpin stator, making the product ready to be assembled in an electric motor.

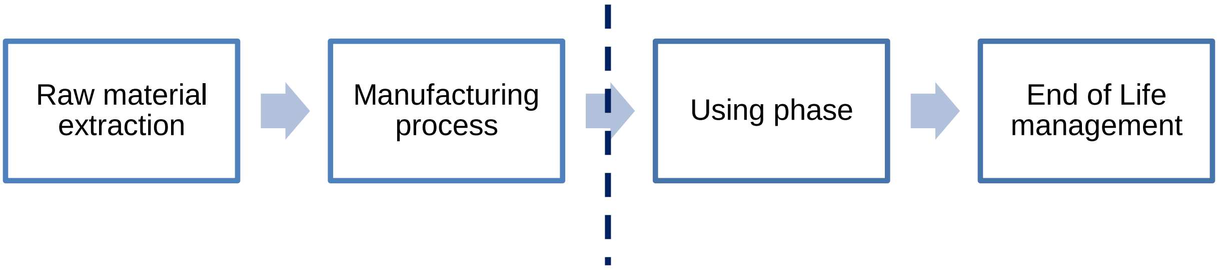

Figure 18: Cut-off point in the LCA[45]

Once, the data approach it is chosen, in turn, these data are shown in two phases, "cut-off cumulative Life Cycle Inventory (LCI)" and "cut-off cumulative Life Cycle Impact Assessment (LCIA)". The difference between them, lies in the scope of the analysis and the specific stage to which the cut-off is applied. Below the characteristic of them are shown:[46]

1) **Cut-off Cumulative LCI**: Refers to an LCI analysis that considers the cumulative environmental impacts until a specific point in the life cycle and excludes the impacts that occur after that cut-off point. This means that the analysis only accounts for the inventory data up to the chosen cut-off time.
2) **Cut-off Cumulative LCIA**: in this phase, the inventory data collected in the LCI phase are translated into potential environmental impacts. "Cut-off cumulative LCIA" refers to an LCIA analysis that considers the cumulative environmental impacts until a specific point in the life cycle and excludes the impacts that occur after that cut-off point. Like the LCI analysis, this means that the LCIA only accounts for the impacts up to the chosen cut-off time.

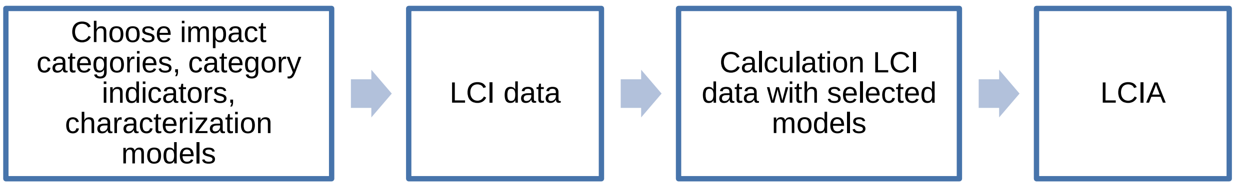

Figure 19: LCIA framework[47]

At the end, the "cut-off cumulative LCIA" approach allows for a more comprehensive assessment of the hairpin stator's environmental impacts because it goes beyond the inventory data and characterizes the environmental impacts associated with the extracted materials and production processes, offering a more holistic understanding

[45] Cf. RWTH (Chair of Production Engineering of E-Mobility Components (PEM)) 2023.
[46] Cf. ScientificDirect (LCA and energy Systems) 2004.
[47] Cf. ScientificDirect (LCA and energy Systems) 2004.

of the product's sustainability. Also, this approach facilitates meaningful comparisons between the hairpin stator and alternative products or manufacturing processes and can reveal the relative environmental performance of the hairpin stator compared to other products or scenarios, helping to drive sustainable design choices.

Finally, this choice is based also in the objectives and questions that were related in the sections before, as finding the answer to how much impact in the environment does the production of the electric power train in the electric drive section (using the hairpin stator as example), the using of these results in another type of electric train production to give conclusions about it or how to find the better ways of production to reduce the impact and find the critical values to improve them.

After the choose of the data approach, it is necessary analyzed and choose the best LCA method to take the data from the eco-Invent data base. There are many of them and bellow it is finding a short definition of each in the table.

Table 4 LCIA methods definitions[48]

CML v4.8 2016	Method from the Center of Environmental Science at Leiden. Evaluates various environmental impact categories like acidification, eutrophication, resource depletion, etc.
Cumulative Exergy Demand (CExD)	Assesses natural resource depletion and energy use efficiency throughout the life cycle.
Ecological Footprint	Measures the demand for natural resources and the Earth's capacity to regenerate those resources
Ecological Scarcity 2021	Assesses the availability of natural resources relative to human demand.
Ecosystem Damage Potential (EDP)	Evaluates potential damage to ecosystems due to emissions and pollution.
EDIP 2003	Assesses environmental impacts in terms of energy and resources.
EF v3.0 and EF v3.1	Evaluate the ecological footprint, i.e., the number of biological resources needed to sustain a product or process.
IPCC 2021	Assessment of impacts from climate change based on reports from the Intergovernmental Panel on Climate Change.
IMPACT 2002+	Assesses various impacts including ecotoxicity, eutrophication, among others.
ReCiPe 2016	Assessment based on characterization factors for diverse environmental impacts.
Selected LCI results	Selected life cycle inventory results.
TRACI v2.1	Tool for the Reduction and Assessment of Chemical and other environmental Impacts. Evaluates various chemical impact categories.
USEtox	Assesses the environmental toxicity of chemical substances.

[48] Cf. EcoInvent 2020.

In the context of this master's thesis, it's crucial to align with the predefined objectives when selecting a method for calculating the impact of hairpin stator production. Upon examining various methodologies, both ReCiPe (Relevance-based impact assessment, Endpoint) 2016 v1.03 and EDIP (Environmental Data and Information Program) 2003 appear suitable for data acquisition. However, they have different approaches and focus on different aspects of impact assessment. Here's a comparison between the two:

1) **ReCiPe 2016 v1.03**
    a) **Methodology:** is a widely used LCIA method that focuses on assessing a comprehensive range of environmental impacts. It considers both midpoint and endpoint impact categories.
    b) **Endpoint Approach:** this one focuses on endpoint impact categories, which are related to specific environmental concerns, such as human health, ecosystem quality, and resources.
    c) **Time Perspective:** it doesn't consider long-term impacts, which means it doesn't necessarily account for effects that occur far in the future.
    d) **Scope:** It covers a broad range of impact categories, including climate change, biodiversity loss, acidification, eutrophication, human toxicity, and more.
2) **EDIP 2003**
    a) **Methodology**: is an LCIA method that primarily focuses on energy and resource-related environmental impacts.
    b) **Resource and Energy Use:** EDIP 2003 specifically emphasizes the impact of resource depletion and energy consumption during a product's life cycle.
    c) **Time Perspective**: It may consider long-term effects due to its focus on resource depletion and energy use, which can have long-lasting consequences.
    d) **Scope**: it places a stronger emphasis on impacts related to energy consumption and the consumption of materials and resources.

After analyzing the different characteristics, both seem suitable for the life cycle of the hairpin stator that is going to be made, however it has been decided to choose the ReCiPe methodology since this focuses on human health, ecosystem quality and the resources. And because the LCA is focus in the first two stages, the acquisition of the raw materials and the production of the hairpin stator, this one is the most suitable one.

Inside the ReCiPe methodology, the data appear in different categories, the terms "endpoint" and "midpoint" refer to different levels of aggregation of impact results. For the analysis of the LCA in the master thesis, it is taken the endpoint data because these shown the end results of each category. Also, the abbreviations "E," "H," and "I" appear to correspond to the three broad impact categories used in this methodology:

- E: Ecosystems
- H: Human Health
- I: Resources

Additionally, "no LT" might indicate the exclusion of certain impact factors within the "Ecosystems" or "Human Health" categories, it means “no long term”. However, it is chosen the opposite methodology, the one without LT because in this LCA it is important the different impacts in the future and the human health.

To sum up, the methodology which the data are taken is ReCiPe 2016 v1.03, endpoint. In the next sections, the data are used to build the LCA of the production of the hairpin stator, with the different steps and after it the results are analyzed in terms of the main objectives.

4 Implementation the Production Process with OpenLCA

Once the data approach and the methodology are chosen, first, it is important to separate the different processes that take place in the production of the stator, to find the different material, machines, and resources necessary for them. The hairpin stator has different parts as for example, the hairpin basket or the electrical sheet pack, which later are assembled to create the final product. In the table below it is watching the final product characteristics.

Table 5: Reference product characteristics[49]

Reference Product	Hairpin Stator
Dimensions	190 mm Ø x 242,5 mm
Location of production process	Cologne (Ford plant)
Weight	35 kg

In this way it is necessary to differentiate the different process to achieve the necessary data. Below are the important characteristics of the three main process to produce the reference product, production of the electrical sheet, production of the hairpin basket and the assembly of them with the insulation paper.

1) **Production of an electrical sheet package**

Table 6: Characteristics of the electrical sheet package production process[50]

Input	**Material**	**Quantity**
	Steel cold rolled coil	6.400.000 mm^3
	Electricity mix	5 kWh
Output	**Material**	**Volume**
	Electrical sheet	1.876.698 mm^3

[49] Cf RWTH (Chair of Production Engineering of E-Mobility Components (PEM)) 2020.
[50] Cf RWTH (Chair of Production Engineering of E-Mobility Components (PEM)) 2020.

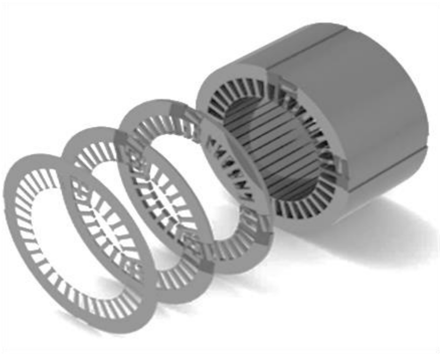

Figure 20: Electrical Sheet[51]

It is crucial to elucidate the utilization of cold-rolled steel coils in the production of electrical sheet packs. As widely recognized, electrical sheet steel typically contains around 2-3% silicon, with a thickness of 0.5 mm, and is cold rolled in a non-oriented manner. Notably, this material comes equipped with lacquer insulation applied to the metal sheet, eliminating the need for an additional consideration in terms of input.

Simultaneously, it holds significance to elaborate on the adoption of an electricity mix as opposed to alternative electricity sources. This decision stems from the fact that the stator's manufacturing location is in Germany. The electricity mix used in Germany refers to the combination of various sources from which the country generates its electrical power. Germany has been a pioneer in transitioning towards a more sustainable and low-carbon energy landscape, aiming to reduce its reliance on fossil fuels and mitigate environmental impact. Here's an overview of the components that typically constitute Germany's electricity mix:[52]

1. Renewable Energy Sources as solar energy, wind power, hydroelectric…
2. Natural Gas, which normally it is only used when renewable production is low.
3. Coal, which it is arranged to reduce and eventually eliminate coal based.
4. Imports, a portion of it from the countries from Europe.

Germany's energy policy, known as the "Energiewende," aims to transition the country towards a sustainable energy future, with a strong emphasis on reducing greenhouse gas emissions and increasing the share of renewables in the energy mix. The specific composition of the electricity mix can vary from year to year based on factors like weather conditions, technological advancements, policy changes, and economic considerations.[53]

At this point it is also important to explain that there is not consideration of material wasting.

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[51] Cf. RWTH (Chair of Production Engineering of E-Mobility Components (PEM)) 2020.

[52] Cf. Statista (Distribution of energy resource in Germany) 2022.

[53] Cf. Statista (Distribution of energy resource in Germany) 2022.

2) **Production of the cooper for the hairpin basket**

Table 7: Characteristics of the hairpin basket production process[54]

Input	**Material**	**Quantity**
	Copper wire	1.043.280 mm³
	Polyamide 6.6	286.793 mm³
	Electricity mix	5.74 kWh
Output	**Material**	**Volume**
	Hairpin basket	1.043.280 mm³

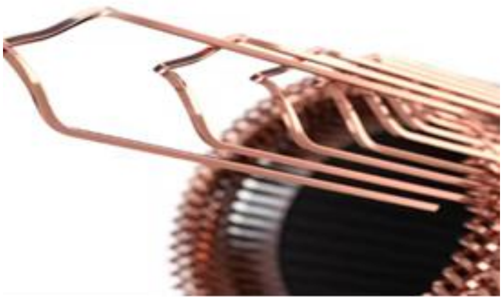


Figure 21: Hairpin basket[55]

In this scenario, it holds significant importance to elucidate the rationale behind opting for the utilization of copper wire. As previously expounded, the copper employed in the process is marketed under the designation SHTherm® 220. This variant essentially comprises enamelled round copper wire encased in a polyamide-Imide insulation. Therefore, within the context of the procedure, the copper wire is employed in conjunction with the inclusion of polyamide 6.6, which serves as the insulating layer.

As previously elucidated, the electricity mix plays a pivotal role in effecting various transformations upon the copper wire. These transformations are instrumental in shaping the wire into the distinctive hairpin basket configuration, involving processes such as cutting, bending, and more.

[54] Cf. RWTH (Chair of Production Engineering of E-Mobility Components (PEM)) 2020.
[55] Cf. RWTH (Chair of Production Engineering of E-Mobility Components (PEM)) 2020.

3) Adding the insulation paper and assembly of the stator

The insulation paper is considered as an input directly, because it is already purchased from the company in the name of DuPont Nomex, so no other process is involved. In the table below, it is shown the characteristics of the assembly process.

Table 8: Characteristics of the hairpin stator assembly process.[56]

	Material	**Quantity**
Input	Insulation paper	85.489 mm³
	Electrical sheet	6.400.000 mm³
	Hairpin basket	1.043.280 mm³
	Polyamide 6.6 fibres	8064 mm³
	Polyester resin	6 kg
	Electricity mix	17.25 kWh
Material waste	Not considered	
Output	1 item of hairpin stator	

Figure 22: Hairpin stator[57]

It is important to know that contact rings, jumpers, connection terminals... Are also part of the production of the hairpin stator, however these will not take an important place in the process, and they will not be considered on it. At the same time, to prevent short

[56] Cf. RWTH (Chair of Production Engineering of E-Mobility Components (PEM)) 2020.

[57] Cf. GROB (Electric motors and E-machines)

circuits, a powder coating of resin is applied to the bare copper ends that make contact. Approximately 56 mm³ of powder coating is required per contact point, with a total of 144 contact points to be coated, for this it has been used the polyamide 6.6 fibers, because it is working with the same characteristics as the used in the process. And the product used for the coating is ResiCoat e-lock® from AkzoNobel, which in this case it will be considered as a polyester resin, because from the data sheet it is an epoxy powder coating use in a wide variety of electrical, mechanical, and chemical applications[58], and this product is the most like it.

It's needed to create the three different processes to create the final products named up:

1) Production of the metal sheet
2) Production of the hairpin basket
3) Assembly of the hairpin stator

Finally, the Hairpin Stator as a product System is created. In the figure bellow is shown how the process looks once its finally implemented and the relations in each process between the inputs and the outputs.

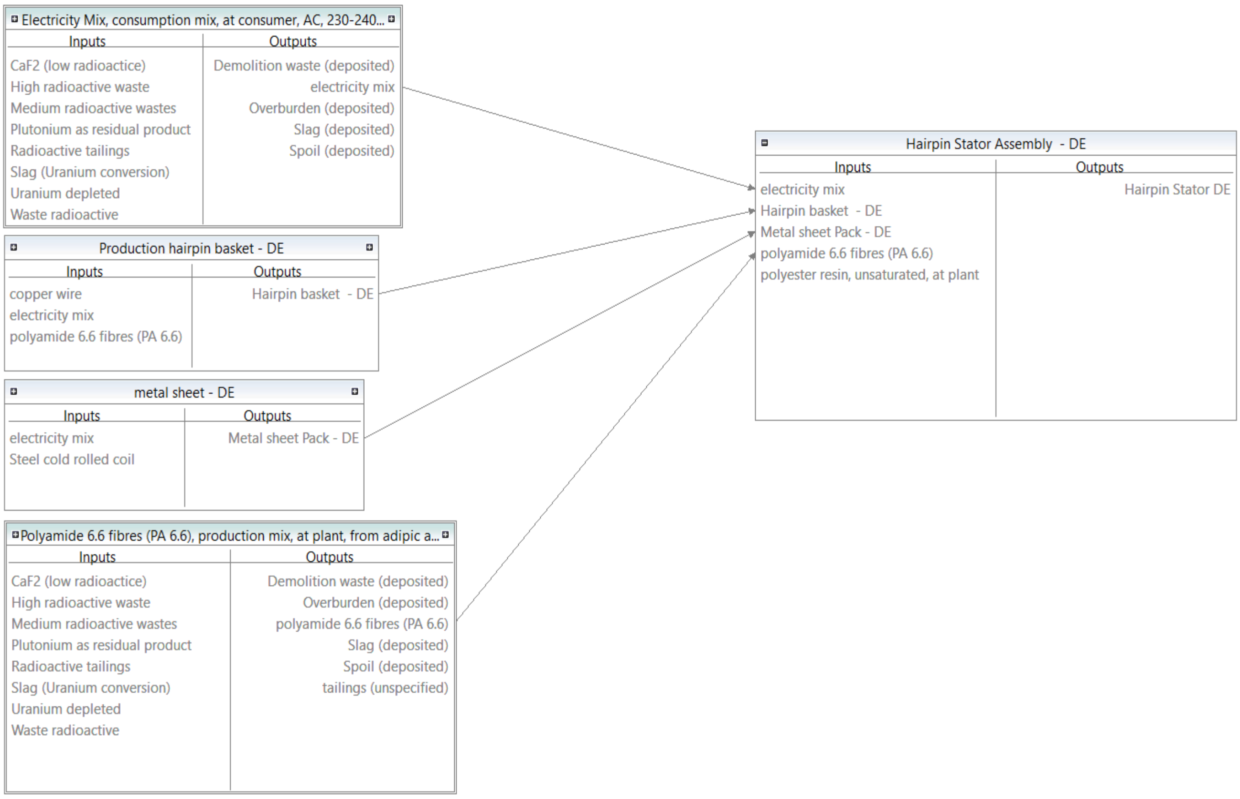


Figure 23: Hairpin stator model graph from OpenLCA.

[58] Cf. AkzoNobel (ResiCoat).

Once the process is defined, is time to collect the data from the Eco-invent data base and go ahead with the simulation of the LCA, to take the important date from it and analyse the impact of the hairpin stator production.

It's worth noting that the cost calculation is not included in this work. Furthermore, the method used has already been explained in the previous section, and the endpoint recipe will be used. However, it is necessary to make one more division within this method, since it is divided into three categories depending on the objective of the analysis, which are explained bellow:[59]

1) **Recipe Endpoint H, A (Harm to Air):** This method focuses on assessing environmental impacts related to the emission of harmful substances into the atmosphere, such as greenhouse gases (GHGs), nitrogen oxides (NOx), sulfur oxides (SOx), and other atmospheric pollutants. Therefore, it centers on environmental impacts affecting air quality.
2) **Recipe Endpoint I, A (Harm to Ingestion of Air and Water):** This method addresses a broader range of impacts, including those related to both air and water quality. In addition to considering atmospheric emissions, it also evaluates the effects on water quality that may result from substances released into the air and subsequently deposited into bodies of water. This means it considers atmospheric deposition and its effects on water quality.
3) **Recipe Endpoint E, A (Harm to Ecosystems and Human Health):** This method is the most comprehensive of the three and considers a wide range of environmental impacts. In addition to impacts on air and water quality, it also assesses effects on terrestrial and aquatic ecosystems as well as human health. This means it includes evaluations of how chemicals and substances released into the environment can impact biodiversity and human health.

As the main objective of this thesis is the analysis of the impact of production on the ecosystem and on human health, the appropriate method for analyzing will be the last one, the Recipe Endpoint E, A, as this is the most complete of them.

Once it has carried out the simulation, different results are obtained from different categories of impacts, among which the following stand out:

Attending to the Ecosystem Quality:

1) **Agricultural Land Occupation:** This impact category assesses the amount of agricultural land occupied or degraded because of the production of the stator. The occupation of agricultural land can have adverse effects on land availability for food and other crop production.

[59] Cf. National Institute for Public Health and the Environment (Recipe 2016) 2016.

2) **Climate Change, Ecosystems:** It evaluates the impact of climate change on natural ecosystems. This includes effects such as rising temperatures, altered precipitation patterns, and habitat loss due to climate change.
3) **Freshwater Ecotoxicity:** This measures the toxicity that emissions of substances into freshwater ecosystems, such as rivers and lakes, can have on aquatic life.
4) **Freshwater Eutrophication:** It assesses the impact of eutrophication in freshwater bodies, which occurs when there is an excess of nutrients, such as nitrogen and phosphorus, in the water. This can lead to algal blooms and the degradation of aquatic ecosystems.
5) **Marine Ecotoxicity:** Like freshwater ecotoxicity, this impact category assesses the toxicity of emissions on marine ecosystems, including seas and oceans.
6) **Natural Land Transformation:** This measures the conversion or degradation of natural ecosystems, such as the transformation of pristine lands into urban or agricultural areas.
7) **Terrestrial Acidification:** It evaluates the acidification of terrestrial ecosystems primarily caused by emissions of acidic compounds, which can harm vegetation and soils.
8) **Terrestrial Ecotoxicity:** This measures the toxicity of emissions in terrestrial ecosystems, including potential toxicity to land-based fauna and flora.
9) **Urban Land Occupation:** It assesses the amount of land occupied or degraded due to urban activities, such as construction and infrastructure related to stator production.
10) **Total:** This is the overall result that combines all the above impacts related to ecosystem quality.

In case of the Human Health:

1) **Climate Change, Human Health:** It evaluates the impacts of climate change on human health, including effects like heat-related illnesses, extreme weather events, and changes in disease distribution.
2) **Human Toxicity:** This measures the toxicity of substances released during stator production and their potential impact on human health.
3) **Ionising Radiation:** It assesses the effects of ionizing radiation on human health, which may be related to processes involving radioactive materials.
4) **Ozone Depletion:** It evaluates the degradation of the stratospheric ozone layer and its potential effects on human health, such as increased exposure to ultraviolet radiation.
5) **Particulate Matter Formation:** This measures the formation of airborne particulates that can have adverse effects on human respiratory health.

6) **Photochemical Oxidant Formation:** It assesses the formation of photochemical oxidants in the atmosphere, which can contribute to health issues like smog and respiratory irritation.
7) **Total:** This is the overall result that combines all the impacts related to human health.

And finally, about the Resources:

1) **Fossil Depletion:** This measures the depletion of fossil resources, such as oil and natural gas, used in stator production.
2) **Metal Depletion:** It evaluates the depletion of metals used in stator production, such as iron and copper.
3) **Total:** This is the overall result that combines all the impacts related to the depletion of natural resources.

The last indicator refers to the complete process:

Total: This global result combines all the impacts assessed in the life cycle assessment, encompassing ecosystem quality, human health, and resource depletion, providing an overview of the environmental and health impacts of stator production.

The results of each category are discussed in the sections bellow.

5 Impact calculation results

In this section the result obtained in the simulation are shown and the correspondent commentaries and deductions found, making distinction in the main three impact categories, ecosystem quality, human health, and resources.

5.1 Ecosystem Quality

In the pursuit of sustainable industrial practices, it is crucial to assess the potential impacts of production processes on the environment, with a specific focus on ecosystem quality. Hairpin stator production, a vital component of electrical machinery, is no exception to this evaluation.

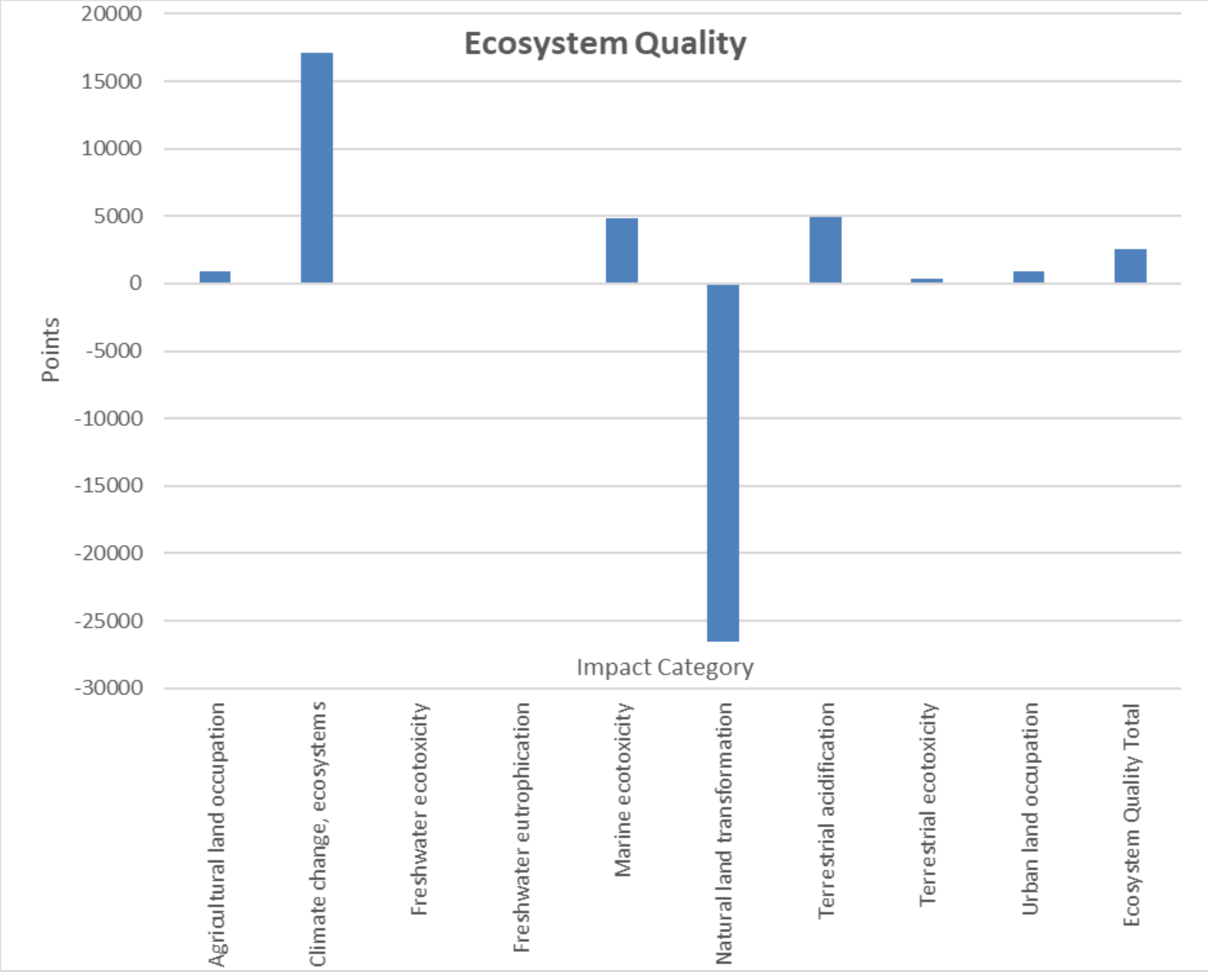
Ecosystem quality impact assessment within the realm of hairpin stator production serves as a vital tool for understanding the potential consequences of this manufacturing process on natural ecosystems, biodiversity, and the overall health of the environment. This assessment involves scrutinizing various factors, including emissions, resource consumption, land use, and their potential impacts on terrestrial, aquatic, and marine ecosystems[60].

This comprehensive analysis aims to answer pivotal questions: What ecological risks are associated with hairpin stator production? How can you minimize these impacts and promote sustainable practices that preserve and protect the ecosystems? Once the analysis of the LCA has been finished, the results for the different impact categories are found in the table below.

[60] Cf. LC-Impact (Ecosystem Quality)

Table 9: Ecosystem quality impact categories results

	Impact category	Points	Commentaries
Ecosystem Quality	**Agricultural land occupation**	893	Positive value indicates an increase in the occupation of agricultural lands due to the production of the hairpin stator.
	Climate change, ecosystems	1.7154,63	It’s a high value, suggesting a significant impact on ecosystems due to climate change.
	Freshwater ecotoxicity	0,28	Compare with other values its low, so the impact of the ecotoxicity on freshwater is low according to the production of the hairpin stator.
	Freshwater eutrophication	9,55 E-05	It is an exceptionally low value, suggesting minimal impact on freshwater eutrophication, as the one before.
	Marine ecotoxicity	4.826,66	It is a significant value, suggesting a considerable impact on marine ecosystems.
	Natural land transformation	-26.516,2	the value is it negative, this shows the regeneration of natural lands instead of degradation due to stator production.
	Terrestrial acidification	4.966,2	Indicates a high impact of acidification on terrestrial.
	Terrestrial ecotoxicity	379,87	This shows that there is an impact on the Ecotoxicity but isn’t as important as the acidification shown before.
	Urban land occupation	893	The value is considered high, which means that the production of the hairpin stator affects the occupation of the urban land

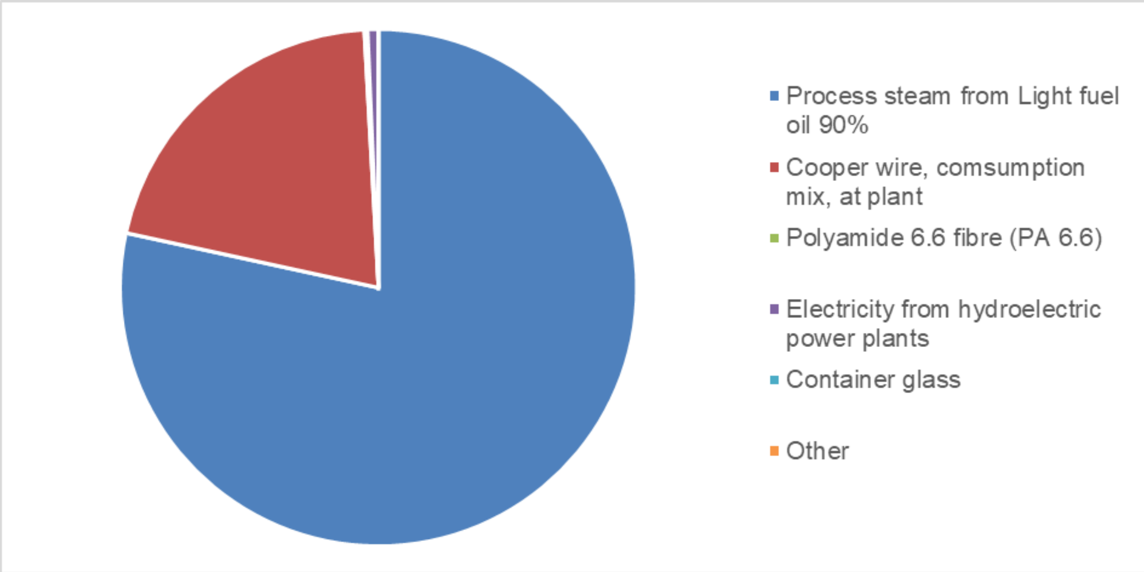


Graphic 5: Ecosystem quality impact categories results

After conducting a comprehensive analysis of the overall process, it is essential to proceed with a more focused study of specific processes that have a greater impact on the results. As demonstrated, the category with the highest results is 'Climate Change, Ecosystem.' When analysing this category, it becomes evident that the processes exerting the most significant influence on it are shown in the next table.

Table 10: Top 5 process contributions to total ecosystem quality category

Process	Points
Process steam from Light fuel oil 90%	5.885
Cooper wire, consumption mix, at plant	1.555
Polyamide 6.6 fibre (PA 6.6)	15,692
Electricity from hydroelectric power plants	-50,421
Container glass	-0,0034
Others	0,039



Graphic 6: Top 5 contributions to impact on ecosystem quality total

5.2 Human Health

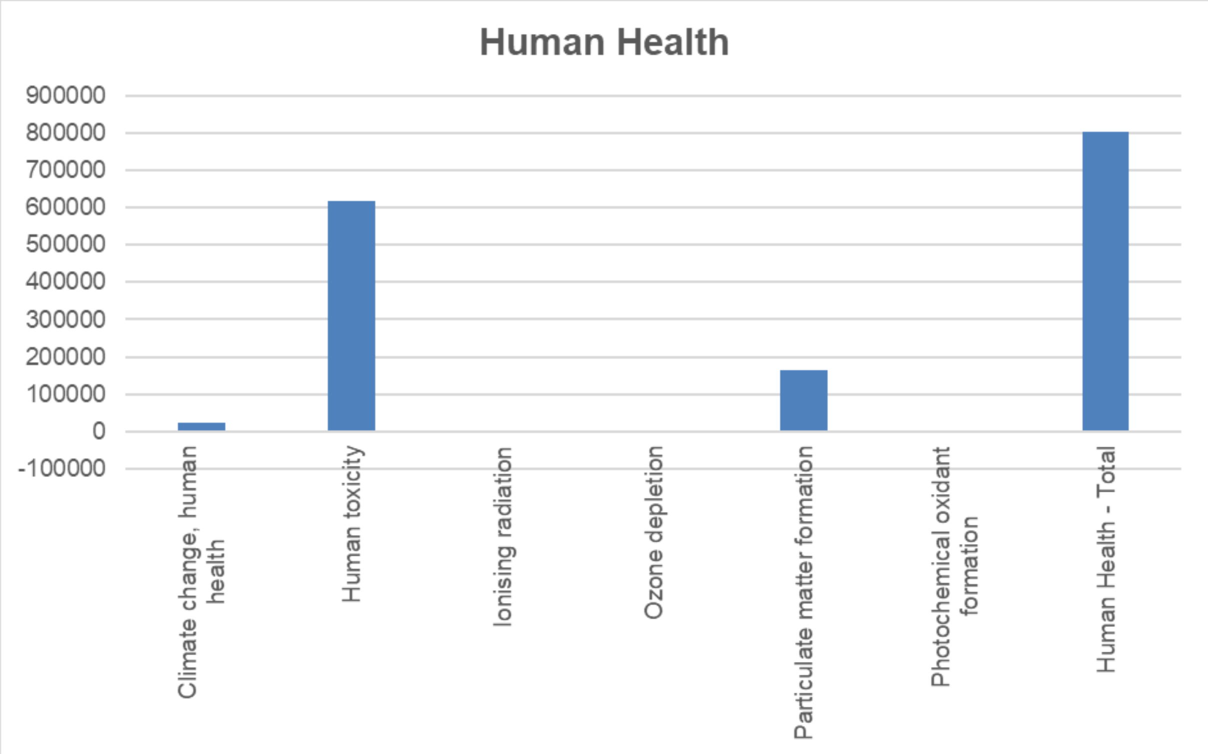
As in the category ecosystem quality, in the quest for more sustainable and environmentally responsible industrial practices, it has become increasingly essential to assess the potential impacts of various processes on human health.

Human health impact assessment within the context of hairpin stator production serves as a fundamental tool for understanding the potential consequences of this manufacturing process on the well-being of workers, local communities, and the broader population. This assessment involves evaluating various factors, like exposure to hazardous substances, emissions of pollutants, and potential health risks associated with the entire life cycle of these components.

This comprehensive analysis seeks to address critical questions: What are the potential health hazards associated with hairpin stator production? Are there opportunities to mitigate these impacts and enhance the safety and well-being of those involved in the process? In this exploration of human health impacts within the life cycle assessment framework, different results are achieved, shown in the table below.

Table 11: Human Health impact categories results

	Impact category	Points	Commentaries
Ecosystem Quality	**Climate change**	21.582,96	As this one is high, the impact it is important. It is necessary to clarify that these effects could not include heat-related illnesses, changed in disease patterns and other health-related consequences of warming climate.
	Human toxicity	619.598,87	A high value in this category shows a significant potential for harm to human health due to exposure to toxic
	Ionising radiation	4,41	There is a relative minor impact on human health related to ionizing radiation during the production process of the hairpin stator.
	Ozone depletion	-4,16	A negative value suggests that the production process might contribute to a small degree of ozone layer recovery, which is generally beneficial for human health as it reduces exposure to harmful ultraviolet (UV) radiation.
	Particulate matter formation	162.763,39	Indicate a substantial potential impact on human health due to the formation of particulate matter, which can contribute to respiratory and cardiovascular problems.
	Photochemical oxidant formation	25,68	Moderate impact on human health related to the formation of these oxidants, which can contribute to smog and respiratory issues.



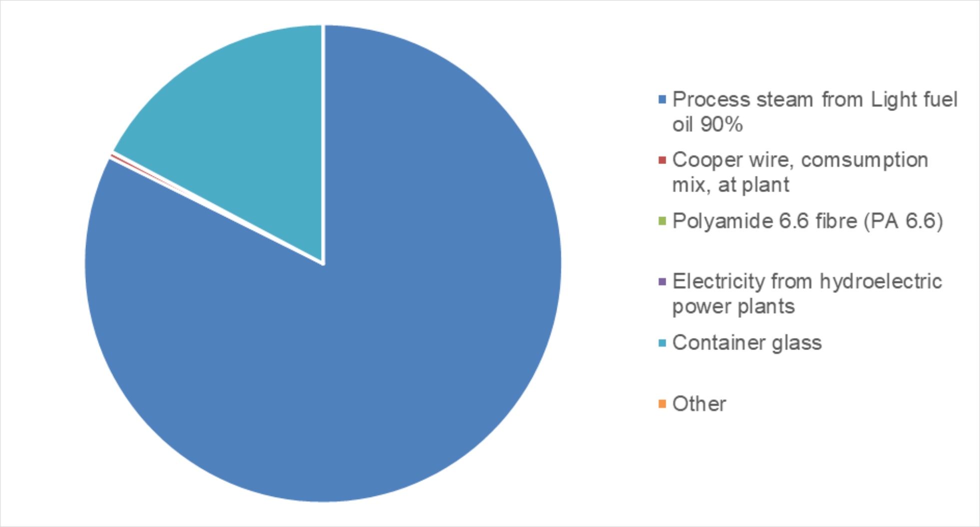
Graphic 7: Human health impact categories results

The results provide a clear view that the production of the hairpin stator has a very high impact on the human health. The efforts should go in the searching of the critical processes and finding new strategies of production to follow, which will reduce the impact on the human health.

So, as it was done in the section before, in this category it is also necessary to do a more detailed analysis about the processes which take more importance in the human health impact. As a result, it is finding, that the processes are the same as in the ecosystem quality category. Finding the results in the table below and represented in the graphic.

Table 12: Top 5 process contributions to total human health category

Process	Points
Process steam from Light fuel oil 90%	5885
Cooper wire, consumption mix, at plant	1555
Polyamide 6.6 fibre (PA 6.6)	15,692
Electricity from hydroelectric power plants	-50,421
Container glass	-0,0034
Others	0,039



Graphic 8: Top 5 contributions to impact on human health total

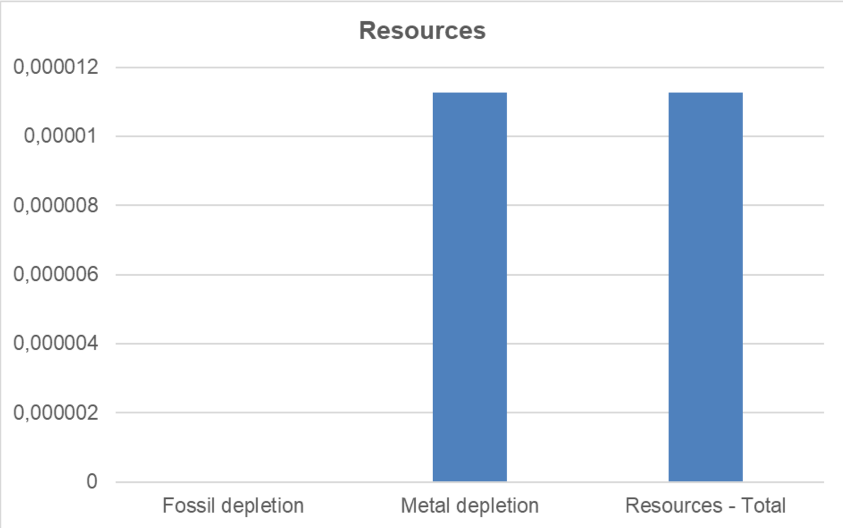
5.3 Resources

The last category serves as a critical lens through which it examines the consumption of resources and their associated environmental consequences. This entails a comprehensive examination of how the production process of hairpin stators interacts with natural resource use, including the extraction, processing, and utilization of materials. It also considers the potential depletion of non-renewable resources and the overall environmental footprint associated with resource consumption.

This analysis seeks to address essential questions: What resources are most significantly impacted by hairpin stator production? How can be minimizing the resource consumption, reduce waste generation, and transition towards more sustainable practices in resource management? The results for the different impact categories are found in the table below and represented in the graphic.

Table 13: Resources impact categories results

	Impact category	Points
Resources	**Fossil depletion**	0
	Metal depletion	1,12 E-05



Graphic 9: Resources impact categories results

As it is finding the impact in the resources is very low, so it makes no sense in this aspect to try to reduce it, because as it was finding in the two categories before, the impact on the ecosystem quality or human health is it considerable bigger than in the resources. So, the efforts will go in the reduction of them.

5.4 Total impact

Mixing the results in one graphic, shown below, the biggest impact about the production of the hairpin stator it is finding in the Human health category. So, the effort should go in the decreasing of them.

Table 14: Impact categories totals results.

Impact category	Points
Total	806568,57
Ecosystem Quality	20597,40
Human Health	8,03E5
Resources	1,12E-5

The process that affects to a greater extend is the “Process steam from Light fuel oil”, that is used in the production process as the vapor is used to heat, sterilize, dry, or drive chemical processes.as for example in the hairpin stator process once the insulation paper is added, is needed to cover this with a resin, as was explained in the sections before. In this process is needed the heating from the vapor. However, this is only one example of the use of it, there are many processes that uses it.

6 Discussion of the results and Solutions Proposal

In this section, it will delve into a range of strategic solutions aimed at minimizing the impact identified in the previous analysis. These solutions have been developed with the goal of effectively addressing the main objective of this thesis, find solutions to reduce the impact of the production of the e-drive train components.

As found, the process with the highest environmental impact is the 'Process steam from Light fuel oil 90%, consumption mix, at power plant, heat plant, MJ, 90% efficiency.' To reduce this impact, it is essential to explore new alternatives that can provide the same energy required for production. Some of them are proposed:

1) **Transition to Renewable Energy sources**
    - Using renewable energy sources like solar or wind energy, to generate the required steam.
    - Reduce carbon emissions and other environmental impacts.
2) **Improving Energy Efficiency**
    - Evaluate the possibility of increasing the efficiency of the steam generation process.
    - Upgrading equipment and technologies to reduce fuel consumption per unit of steam produced.
3) **Optimize Fuel Sources**
    - Investigate the use of cleaner or more sustainable alternative fuels instead of light fuel oil.
    - Biofuels or lower-impact synthetic fuels.
4) **Recovery of Waste Heat**
    - Recovering and utilizing waste heat from the steam generation process for other applications within the plant, such as building heating or industrial processes.
    - Maximize energy efficiency.
5) **Logistics and Transport Optimization**
    - Assess the efficiency of fuel logistics and transportation to the plant.
    - Reducing transportation distances and using cleaner transportation methods can decrease environmental impact.
6) **Technological Innovation**
    - Stay informed about technological innovations in energy generation and steam processes.

In the pursuit of reducing the environmental impact associated with hairpin stator production at a Ford factory in Cologne, Germany, there are presented several viable strategies and options. Among these options, it has carefully considered the implementation of a cogeneration system that captures both heat and electricity generated during the production process.

This choice has been made after thorough analysis, considering various factors, and it is poised to bring significant environmental benefits to the manufacturing process. The implementation of a cogeneration system aligns with the broader goals of sustainability, energy efficiency, and reduced environmental impact. Here's why this strategy has been chosen[61]:

a) **Efficiency Enhancement:** Cogeneration allow to maximize the utilization of energy resources. By capturing and utilizing both heat and electricity generated during the hairpin stator production, can significantly improve the overall efficiency of the manufacturing process. This means that it is getting more out of the energy inputs, which translates to reduced resource consumption and lower emissions.
b) **Reduced Reliance on External Energy Sources:** A cogeneration system reduces the reliance on external energy sources, such as fossil fuels or grid electricity. By generating their own power and heat on-site, it is gaining independence and resilience against fluctuations in energy prices and supply disruptions.
c) **Lower Emissions:** One of the most compelling reasons for choosing cogeneration is its positive impact on emissions reduction. By efficiently utilizing fuel for both electricity and heat production, it can cut down on greenhouse gas emissions and other pollutants associated with energy generation. This aligns with the commitment to combat climate change and improve air quality.
d) **Environmental Responsibility:** Implementing a cogeneration system reflects the dedication to environmental responsibility and sustainable manufacturing. It demonstrates the proactive approach to reducing the environmental footprint of these operations, which is essential not only for regulatory compliance but also for meeting the evolving expectations of consumers and stakeholders.

Additionally, upon implementing the cogeneration system, it is possible to anticipate several key improvements and benefits[62]:

[61] Cf. COGEN Europe. (What is Cogeneration?) 2020
[62] Cf. COGEN Europe (What is Cogeneration?) 2020

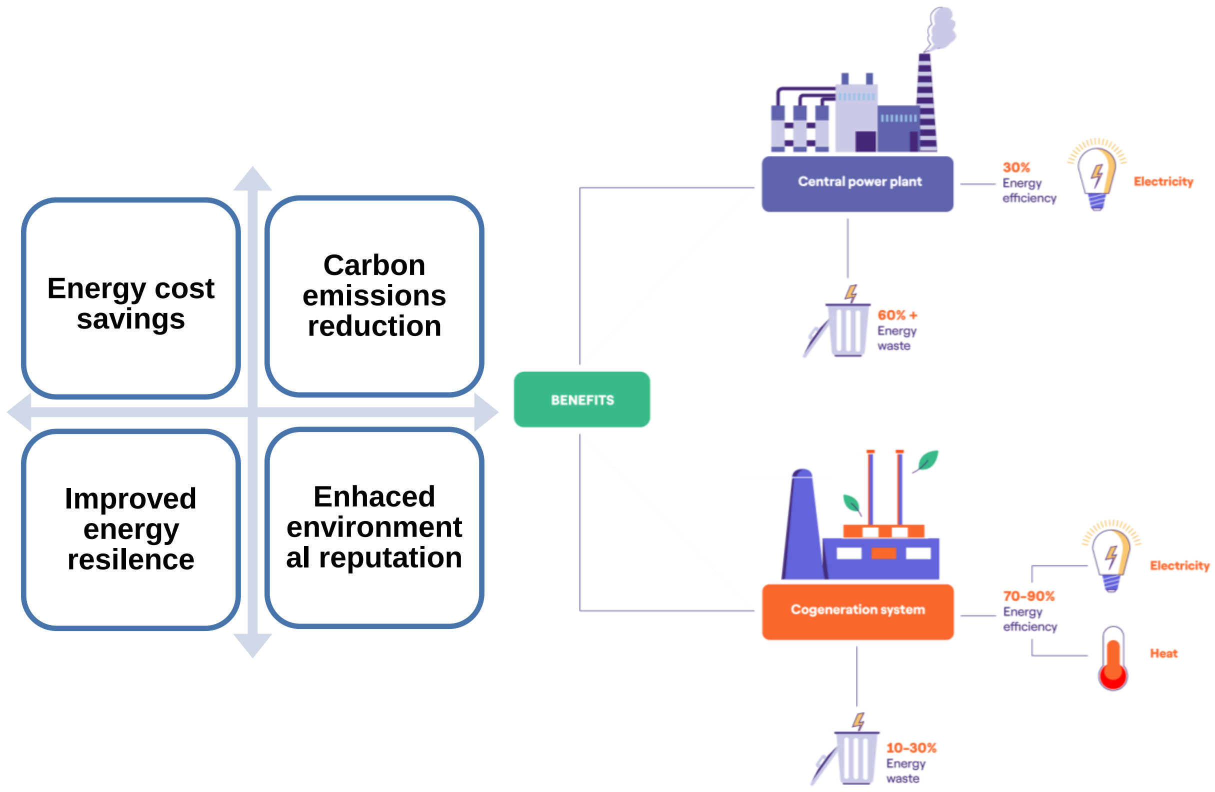


Figure 24: Cogeneration benefits vs central power plant[63]

In conclusion, the selection of a cogeneration system for stator production in the Ford factory in Cologne, Germany, is a well-considered and strategic choice. This environmentally friendly approach aligns with the commitment to sustainability, efficiency, and emissions reduction, benefiting both the operations and the environment. By implementing this system, it is taking a significant step towards a greener and more sustainable future for the manufacturing processes of the hairpin stator.

Furthermore, it is essential to consider the use of renewable energy sources, given the substantial growth in their availability and utilization in recent years. Also opting for green energies reduces the negative effects on air and water quality in the surroundings, as well as it helps with the conservation of the natural landscape.

As it’s shown in the figure bellow, the use of renewables energies in electricity and heat has been increasing in the recent years in Germany, so its important to continue with this increasing.

[63] Cf. EnelX (What are cogeneration systems and what are their benefits?) 2022

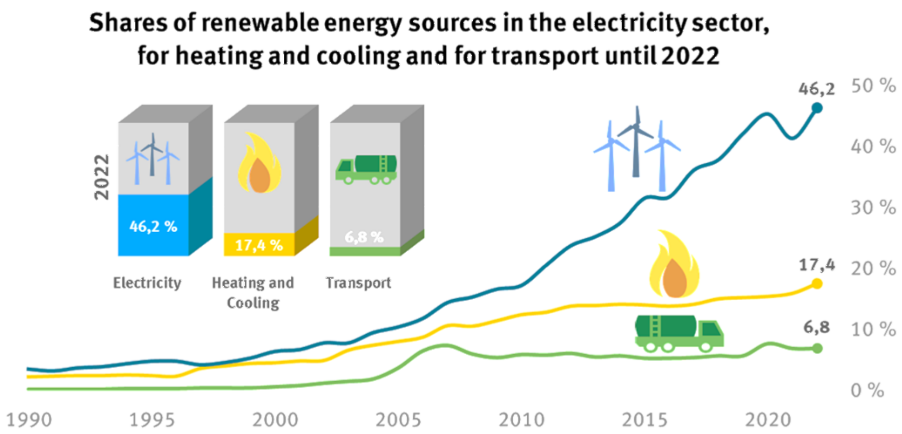


Figure 25: Development of renewable energy shares for electricity, heat, and transport[64]

After the process analyzed, the LCA analysis shown that the consumption of the copper wire it has also a significant impact on the categories. In this context, to reduce the environmental impact associated with this process there are also some strategies to have in consideration:

1) **Copper Recycling**

- Encourage and promote the collection and recycling of copper.
- Ensure that copper waste generated during the process is efficiently collected and recycled.
- Reduce the need for virgin copper extraction and production, thereby decreasing the environmental impact.

2) **Improved Copper Use Efficiency**

- Examine the production process and look for ways to optimize the use of copper in the manufacturing of hairpin stators.
- Implementing more efficient production technologies or designing products that require less copper in their manufacturing.

3) **Use of Recycled Copper**

- Recycled copper instead of virgin copper in the manufacturing of hairpin stators.
- Has a lower environmental impact than copper obtained from minerals.

4) **Exploration of Alternative Materials**

- Investigate the possibility of using alternative materials instead of copper in certain applications within the hairpin stator.

[64] Cf. AGEE-Stat / Umweltbundesamt. 2022.

- Explore the use of less environmentally impactful conductive materials to reduce dependence on copper.

5) **Design Optimization**

   - Optimize the design of hairpin stators to minimize the amount of copper required without compromising product quality and performance.

As in the section before, the selection of specific strategies will depend on the circumstances and resources available at the hairpin stator production plant and the objectives of the thesis. After thorough consideration, it has been opted for the implementation of strategies aimed at the use of recycled copper at the Ford factory in Cologne. The reasons are[65]:

a) **Environmental Impact Reduction:** Copper recycling is one of the most effective ways to reduce environmental impact. By recycling copper and using it instead of virgin copper, the need for additional copper extraction and processing is reduced, lowering the ecological footprint and environmental burden.
b) **Resource Conservation:** Copper is a finite and valuable natural resource. Recycling contributes to resource conservation, ensuring its availability in the long term and reducing pressure on copper reserves.
c) **Less Energy and Emissions:** Producing copper from virgin copper ore consumes a significant amount of energy and emits greenhouse gases. Copper recycling requires less energy and produces fewer emissions, benefiting the environment and climate change mitigation.
d) **Circular Economy:** Implementing copper recycling in the Ford factory in Cologne aligns with the principles of a circular economy, where materials are recycled and reused instead of being disposed of as waste. This contributes to a more sustainable approach to production.
e) **Cost Reduction:** Copper recycling can lead to cost savings in copper procurement, as recycled material is often more cost-effective than virgin copper.

[65] Cf. Cooper Alliance (Cooper Recycling) 2021

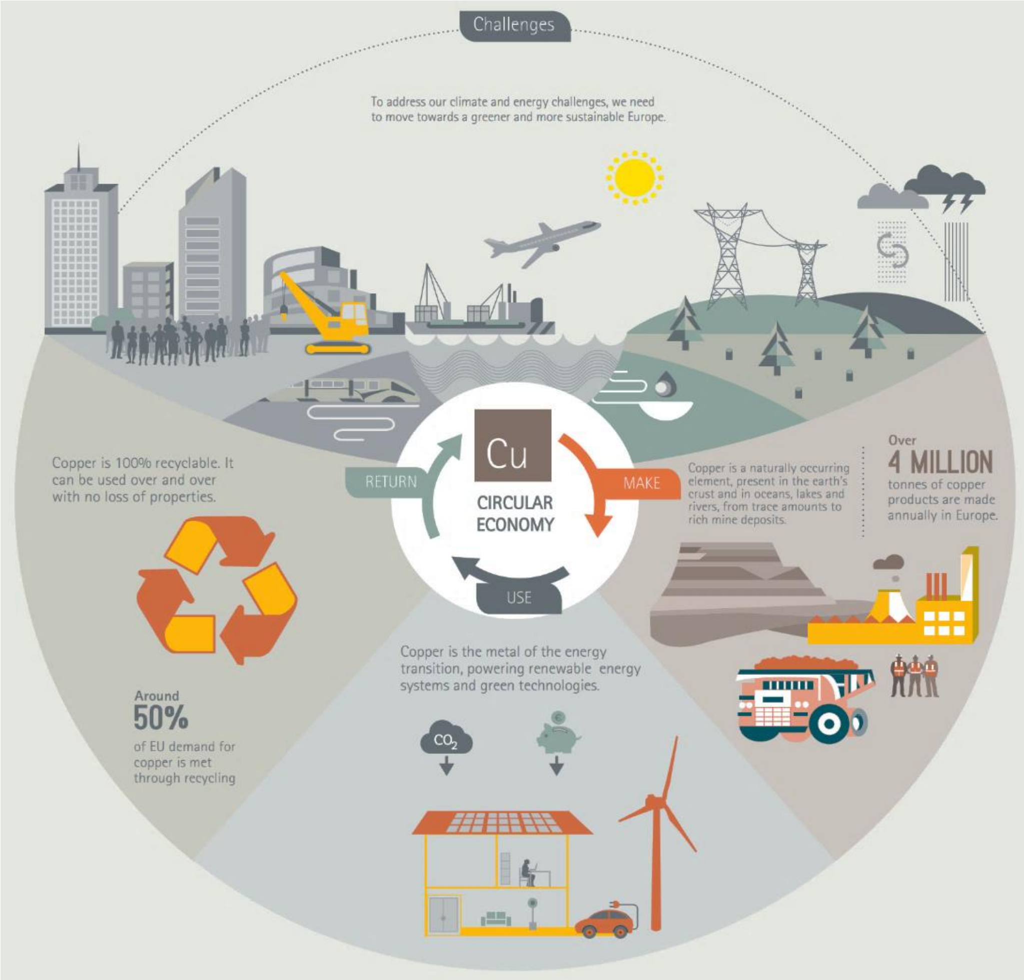


Figure 26: Copper and the circular economy[66]

To implement this strategy, it's important to establish effective copper collection and recycling systems within the factory and foster a culture of responsible resource management. This not only reduces the environmental impact of stator production but may also offer long-term economic benefits.

[66] Cf. European Copper Institute (Copper and the circular acronomy) 2022

7 Conclusions and Future scope

The work provides a comprehensive analysis of the production of a hairpin stator in the context of electric powertrain production within the electric drive sector and it has provided valuable insights into its environmental impact. This study addressed different key questions, which were introduced in the first section.

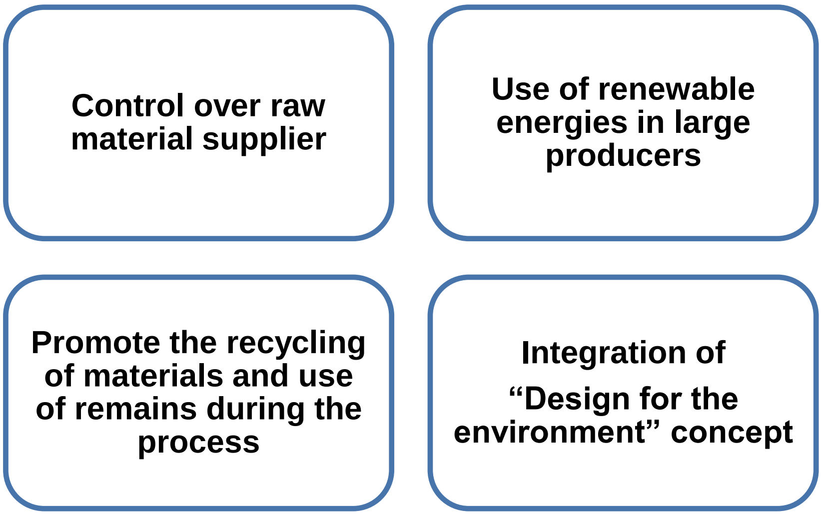
Firstly, about the environmental impact the study unveiled the considerable impact associated with the production of electric powertrains, using the hairpin stator as a representative example. Through the application of LCA methodologies, it quantified the environmental burdens, particularly in terms of ecosystem quality, human health, and resource depletion. While the study focused on the hairpin stator, the conclusions and findings can indeed be extended to other types of electric powertrain production. The principles of LCA and the identified environmental hotspots are transferable, allowing for valuable insights into the broader EVs manufacturing sector.

In this context, the analysis illuminated potential pathways to reduce the environmental impact of electric powertrain production. Strategies such as transitioning to renewable energy sources, improving energy efficiency, recycling materials, and implementing emission control technologies emerged as viable approaches to mitigate impact. Also, the critical processes and flows within the production lifecycle were identified. Notably, the extraction and processing of raw materials, energy-intensive manufacturing processes, and transportation emerged as areas of heightened environmental concern. These critical points highlight specific areas for intervention and optimization.

Looking at all information and results, in my opinion, this study provides a comprehensive understanding of the environmental implications of electric powertrain production, with the example of a hairpin stator. It becomes evident that achieving sustainability in the production of electric drive systems, or any of its components, involves a combination of three fundamental elements: production technology used, materials needed and external factors (as governance). While the aspiration is to achieve complete sustainability in electric drive production, it is important to acknowledge the challenges. In the foreseeable future, achieving full sustainability remains a formidable task, especially considering certain realities:

1) **Mineral Mining Challenges**: Mineral mining, a key component in the production process, remains labour-intensive and poses health risks. The absence of significant design innovations and alternative materials further complicates efforts to make motor production fully sustainable.
2) **Energy Sources:** The widespread reliance on coal as a primary energy source in developed nations, coupled with limited availability of renewable energy options in production, presents obstacles to sustainability.
3) **Complex Supply Chains**: Managing the entire supply chain of any product is a complex undertaking, with an increasing number of variables. Achieving sustainability at every level is challenging.

Considering these complexities, addressing sustainability requires taking incremental steps, focusing on one aspect at a time, and tackling one industry at a time. This approach is essential for filling the substantial void of challenges that currently exists. It's worth noting that smaller firms can pursue sustainable production by considering solutions such as:



To reduce the environmental impact of electric powertrain production, continuous improvement efforts should encompass cleaner energy sourcing, technological innovation, material selection, waste reduction, and responsible supply chain management. However, achieving meaningful reductions in environmental impact, also need collaboration across the electric vehicle industry, involving manufacturers, suppliers, policymakers, and researchers. Sharing best practices and implementing sustainable solutions collectively can drive positive change.

To sum up, looking at the results and exploring the references used on this thesis, it can be said that the automobile industry is consciously moving in the direction of sustainability, looking for sustainable ways of production. However, the process has just begun, and the future is bright.

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